The implications of large-scale irrigated bioenergy plantations for future water use and water stress

Dissertation
zur Erlangung des akademischen Grades

doctor rerum naturalium
(Dr. rer. nat.)

im Fach Geographie

eingereicht an der
Mathematisch-Naturwissenschaftlichen Fakultät
der **Humboldt-Universität zu Berlin**

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Tag der mündlichen Prüfung: 14.09.2021

Fabian Stenzel – 2021
https://doi.org/10.18452/23396

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Abstract

Large scale bioenergy plantations with carbon capture and storage (BECCS) are considered an integral part of most scenarios limiting global warming to below 2 °C or even 1.5 °C, according to the Paris Agreement. To provide sufficient biomass, these plantations are likely to require substantial amounts of freshwater for irrigation which would compete with the projected growing demands from food production, industry, and households. A substantial increase in the water stress for human populations and ecosystems might be the result.

This thesis provides a first systematic assessment of 21st century global irrigation water demands for bioenergy production, for which the current body of literature projects a range of 128.4–9,000 $km^3\ yr^{-1}$. The numbers strongly depend on the parameters and assumptions chosen as well as methodologies and models applied. Systematic simulations for the identified key parameters in the dynamic global vegetation model LPJmL yield that even with optimal bioenergy plantation locations, 1.5 °C can only be reached in scenarios with highly efficient bioenergy systems or strong irrigation expansion without withdrawal limitations. As a result of the large irrigation requirements, a conflict of interest arises between producing sufficient biomass and protecting environmental flows.

A further dilemma is delineated by a comparison of the water stress resulting from the additional irrigation needed to limit climate change and the water stress in a 3 °C warmer world without bioenergy. In both scenarios, the global area and the number of people experiencing water stress would increase severely by the end of the 21st century. The bioenergy scenario shows even higher water stress than the case of unmitigated climate change. Sustainable water management, as a combination of water withdrawal restrictions according to environmental flow requirements and improved on-field water management, has the potential to limit this additional water stress. But it would be a challenge to establish such strategies on a global scale.

This work confirms that in order to provide large amounts of negative emissions, BECCS might lead to undesired deterioration of our environment and impacts for humanity. It further highlights the dilemma of rising water stress regardless whether climate change or climate change mitigation via irrigated bioenergy become a reality. The focus of this thesis is on the dimension of water, but large scale bioenergy production will also affect other aspects such as biodiversity loss as a result of the large land requirements. Thus, mitigation decisions should be based on systemically analysing all social and environmental dimensions of the Earth system.

Die Auswirkungen der Bewässerung von großflächigen Bioenergieplantagen auf den zukünftigen Wasserbedarf und Wasserstress

Zusammenfassung

Die meisten Szenarien, die gemäß dem Pariser Abkommen die globale Erwärmung auf unter 2 °C oder sogar 1.5 °C begrenzen, haben einen hohen Flächenbedarf für Bioenergieplantagen. Um die erforderliche Produktivität zu erreichen, müssten diese Plantagen vermutlich stark bewässert werden. Der Bewässerungsbedarf stünde in Konkurrenz mit dem ebenfalls wachsenden Wasserbedarf von Landwirtschaft, Industrie und Haushalten. Eine erhebliche Zunahme des Wasserstresses für die Bevölkerung und die Ökosysteme wäre die Folge.

Diese Arbeit ist die erste systematische Analyse des globalen Bewässerungsbedarfs für die Bioenergieproduktion des 21. Jahrhundert. In der aktuellen Literatur finden sich diesbezüglich Prognosen von 128.4–9,000 $km^3\ yr^{-1}$. Die Zahlen hängen stark von den gewählten Parametern und Annahmen sowie den angewandten Methoden und Modellen ab. In systematischen Simulationen für die wichtigsten Parameter mit dem globalen Vegetationsmodell LPJmL, ergeben sich zwei mögliche Pfade um die Erwärmung auf 1.5 °C zu begrenzen. Entweder müssten hocheffiziente Bioenergiesysteme entwickelt werden oder es müsste eine unbegrenzte Plantagenfläche bewässert werden dürfen, ohne dabei den Wasserbedarf der Ökosysteme zu berücksichtigen. Letzteres führt zu einem Interessenkonflikt, bei dem die Biomasseproduktion zur Klimarettung auf der einen Seite und der Schutz von Ökosystemen auf der anderen Seite stehen.

Ein weiteres Dilemma wird sichtbar, wenn man den Wasserstress, der sich aus der zusätzlichen Bewässerung ergäbe, mit dem in einer durch ungebremsten Klimawandel um 3 °C erwärmten Welt ohne Bioenergie vergleicht: In beiden Szenarien könnte (im Vergleich zu heute) der Wasserstress bis zum Ende des 21. Jahrhunderts stark steigen. Tatsächlich ergäbe sich im Bioenergie-Szenario aber sogar potenziell mehr Wasserstress als im Klimawandel-Szenario. Nachhaltiges Wassermanagement als Kombination aus Wasserentnahmebeschränkungen gemäß den Anforderungen von Flussökosystemen und verbessertem Wassermanagement auf agrarischen Nutzflächen hätte das Potenzial, diesen zusätzlichen Wasserstress zu begrenzen, wäre jedoch auf globaler Ebene schwierig zu etablieren.

Diese Arbeit bestätigt, dass Bioenergieplantagen neben den Negativemissionen, die sie liefern sollen, auch zu unerwünschten Nebenwirkungen in anderen Dimensionen des Erdsystems führen könnten. Neben dem Thema Wasser stellt z.B. auch der Biodiversitätsverlust durch Landumwandlung ein ernstes Problem dar. Daher sollten zukünftige Entscheidungen über Negativemissionstechnologien auf der systemischen Analyse aller sozialen und ökologischen Dimensionen des Erdsystems beruhen.

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For Tabea

Acknowledgements

Writing this thesis would not have been possible without the help and support of many colleagues, friends, and my family. I am deeply indebted to them all.

First and foremost, I want to thank you, Dieter, for the opportunity to write this thesis and the great supervision and support during the past years. I am very grateful for the freedom you gave me to explore my own ideas, while at the same time always having an open door, ear, or mail inbox for questions.

I very much enjoyed working in the TESS team and thank all members for the support and the company. Vera, Jonas, Sibyll, and Sebastian, without your LPJmL kickstart and the constant support I would have been lost. Thank you, Wolfgang, for your support and trust. I am also grateful to all members of the LUCHS group for listening to my ideas and giving critical and constructive feedback. This thesis would not have been possible, without simulation and visualisation on the high performance cluster of PIK. Thanks for providing this great infrastructure!

Furthermore, I want to thank the organisers and members of my graduate school IRI THESys, IIASA's YSSP cohort of 2019, and the SPP 1689, especially Kathrin, Ulrike, Tanja, and Aleks. Thank you for all the workshops and other opportunities to meet and exchange, especially those that were not exclusively about science.

I thank Martina Flörke, Sabine Fuss, and Tobias Krüger for their interest and time, to act as referees in my PhD committee.

For the final stages of preparing this thesis, I thank you, Irmgard, Rebekka, and Safa, for your patience and time while reviewing my drafts. Nele, Jonas, Juri, Hanno, and Martin, thank you, above all, for your company and support. Renate and Wolfgang, without you all this would not be possible. And thank you, Tabea, for always standing by my side!

A final big Thanks goes to all the numerous people who contributed to this work but are not mentioned herein.

Thank you!

Table 1: List of abbreviations and units

AEI	Area equipped for irrigation	ISI	International Scientific Indexing
AR	Afforestation and reforestation	ISIMIP	Intersectoral Impact Model Intercomparison Project
AR5	Fifth assessment report of IPCC		
BE	Bioenergy	iwue	Inverse water use efficiency
BECCS	Bioenergy with carbon capture and storage	km^3	Cubic kilometres
beY	Bioenergy plant yield	LPJmL	Lund-Potsdam-Jena managed Land model
BP	Bioenergy plantation	LUC	Land-use change
C3	"Classic" pathway of photosynthesis	LUdiff	Land-use difference
C4	"More efficient" pathway of photosynthesis	LULCC	Land-use and land-cover change
CC	Climate change	MAF	Mean annual flow
CCdiff	Climate change difference	MAgPIE	An agro-economic model
CCS	Carbon capture and storage	Mha	Mega hectare ($10^{10} m^2$)
CDR	Carbon dioxide removal	MIRCA	Monthly irrigated and rainfed crop areas
CE	Climate engineering	MMF	Mean monthly flow
c_{eff}	Carbon conversion efficiency	MONET	A value chain model
CH_4	Methane	NE	Negative emission
CMIP	Coupled Model Intercomparison Project	NET	Negative emission technology
CO_2	Carbon dioxide	nY	Net yield
cons	Consumption	oCDR	Oceanic carbon dioxide removal
CROPWAT	Agricultural decision support tool	PanClim	PAtterN scaling CLIMate dataset
DAC	Direct air capture	PB	Planetary boundary
DACCS	Direct air capture and carbon storage	PIK	Potsdam Institute for Climate Impact Research
DFG	German Research Foundation		
DGVM	Dynamic global vegetation model	POEM	Potsdam Earth Model
DM	Dry matter	ppm	Parts per million
EF	Environmental flow	PyCCS	Pyrogenic carbon capture and storage
EFR	Environmental flow requirement	REMIND	An energy-economy model
EJ	Exa joule (10^{18} joule)	RCP	Representative concentration pathway
ESM	Earth system model	RF	Rainfed
ET	Evapotranspiration	SCE	Soil carbon enhancement
EW	Enhanced weathering	SDG	Sustainable development goal
GCAM	Global Change Analysis Model	seq	Carbon sequestration
GCM	General circulation model	SPP	Priority Program
GDP	Gross domestic product	SRM	Solar radiation management
Gha	Giga hectare ($10^{13} m^2$)	SSA	Sub-Saharan Africa
GMT	Global mean temperature	SSP	Shared socioeconomic pathway
GtC	Giga tons carbon (10^9 tons carbon)	SWM	Sustainable water management
$GtCO_2$	Giga tons CO_2 (3.66 $GtCO_2 \widehat{=} 1$ GtC)	tCDR	Terrestrial carbon dioxide removal
GWAM	Global Water Availability Model	TechUp	Technology advanced pathway
HIL	Households, industry, livestock	tY	Timber yield
H08	A Hydrological model	VISIT	Terrestrial ecosystem model
HYDE	History Database of the Global Environment	VMF	Variable Monthly Flow method
IAM	Integrated assessment model	WaterSIM	Water balance model
IBdiff	Irrigated bioenergy difference	wd	Withdrawals
IPCC	Intergovernmental Panel on Climate Change	WM	Water management
IRR	Irrigation	WS	Water stress
IrrExp	Irrigation Expansion	WSI	Water stress index
irr_{frac}	Irrigation fraction	yr	Year

1 Introduction

1.1 Large scale human interventions with the Earth system

1.1.1 Where it all began: Land-use change

Large scale human interference with the Earth system has a long history. For millennia, humans have been converting natural ecosystems to address their needs (Goldewijk and Ramankutty, 2009). What began with controlled fires to clear savannahs for hunting, led to the Neolithic Revolution where humankind started to settle and consistently used surrounding areas for crop cultivation and pastures (Weisdorf, 2005). Subsequently, large scale deforestation happened in several world regions for military or construction purposes (Pongratz et al., 2008; Goldewijk and Ramankutty, 2009; Harris, 2013). The hunger for wood originating in colonialism and the industrial revolution sped up the conversion of natural land, so that in the early 20th century a worrying mark was passed. More than 50 % of Earth's ice-free surface is now under anthropogenic land use (Ellis et al., 2010).

In retrospect, the year 1700 marks an equally important transition for land-use research, not only in first signs of an acceleration in global scale land-use change, but also with an increasing availability of data collected for statistical purposes, such as population or economic records. Consequences of large scale land-use change (LUC) include soil degradation (Goldewijk and Ramankutty, 2009) as well as the alarming decline in terrestrial biodiversity (Newbold et al., 2015), due to habitats changing beyond the adaptive capacities of many species. Additionally, LUC accelerates fossil fuel emission-driven climate change (CC) by increasing atmospheric green house gas concentrations through direct release or the weakening of land sinks (Le Quéré et al., 2009). For the decade 2009–2018, emissions from land use and land-cover change (LULCC) with (1.5 ± 0.7) GtC comprise 13 % of total CO_2

emissions, yet for cumulative emissions from 1750–2018, LULCC emissions make up a third of all CO_2 emissions (Friedlingstein et al., 2019), which indicates that historically the climate response was dominated by the rise in CO_2 caused by LULCC emissions (Pongratz et al., 2010). Overall, LULCC and CC have led to major ecosystem shifts on more than 90 % of all areas cultivated, corresponding to 26 % of the total land area, according to the Γ-Metric (Heyder et al., 2011). Also for Γ, LULCC since 1700 are considered a major shock to ecosystems, however impacts from CC have reached similar levels within just one century (Ostberg et al., 2015).

1.1.2 Modification of the water cycle

The ever increasing food demand of a growing population could not be fulfilled by increasing agricultural areas alone, but also drove management practices to increase the per hectare productivity. Besides the industrial production of fertilizer, large scale irrigation is the most widely used measure to increase productivity on cropland (Siebert and Döll, 2010). From 1900 to 2005, the global extent of area equipped for irrigation (AEI) increased from 63 Mha to 306 Mha (Siebert et al., 2015), thereby increasing agricultural water withdrawals from about 500 to 3,000 $km^3\ yr^{-1}$ (Döll and Siebert, 2002; Moe and Rheingans, 2006; Jägermeyr, 2020). It is challenging to estimate historic water use, since the absolute global amounts have not been recorded. Therefore, reconstructions are based on global models fed with assumptions about historic local population, precipitation, and water use efficiency on AEI to estimate the global numbers. Figure 1.1 shows the difference between such simulations, (a) limited by the surface water availability and (b) with unconstrained irrigation with as much water as the plants need, highlighting potential additional groundwater abstractions for irrigation to fill the gap. The total historic water use differs by a factor of up to 2, depending on this choice. The consequences are water scarcity and transgression of environmental flow requirements (EFRs) in many river basins worldwide, especially in the Mediterranean region, the Middle East, Pakistan, India, Northeast China, and the Western United States (Alcamo et al., 2003; Jägermeyr et al., 2017). On top of the irrigation, other sectors, including industry, households, and livestock also demand water in the order of 1,000 $km^3\ yr^{-1}$ (in the year 2005) (Flörke et al., 2013).

Meeting this demand has lead to the construction of more than 50,000 large dams and reservoirs, increasing the share of irrigation water supplied by reservoirs from 5 % to 40 % during the 20th century (Biemans et al., 2011). Dams and reservoirs provide water and electricity, however at the same time disrupt the ecological connectivity of rivers and modify quantity, quality, and timing of the discharge (Lehner et al., 2011). In this thesis I focus on river discharge as a proxy for freshwater availability, water use and depletion of natural water resources.

Besides the destruction of habitats in the valleys which are used as reservoirs, sudden changes in quantity and timing of river flow, as a result of dams, pose severe problems to established aquatic ecosystems (Poff and Hart, 2002; Schmutz and Moog, 2018).

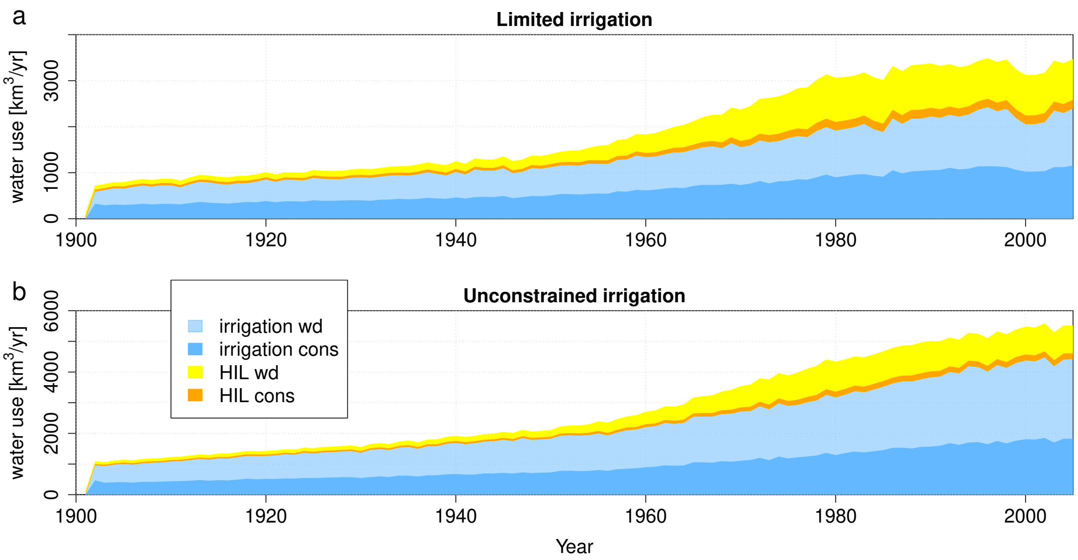


Figure 1.1: Historic water use based on simulations with LPJmL using a land-use dataset including historic area equipped for irrigation classified into 3 irrigation systems based on MIRCA2000 (Portmann et al., 2010; Jägermeyr et al., 2015). Irrigation in the model is either **a)** limited by the available surface water, or **b)** unlimited (including groundwater, redirected water), yielding differences of a factor of up to 2. HIL water use is based on (Flörke et al., 2013).
cons: consumption; HIL: households, industry, livestock; wd: withdrawals

However, not only the existence of dams and reservoirs modifies river flow, but also large scale upstream water use (partially only possible through dams and reservoirs) reduces the available water volume (Neumann et al., 2011). To estimate the flow requirements of aquatic ecosystems and quantify their transgressions, the concept of EFRs was established. EFRs appropriate a portion of the natural stream-flow to the environment (Postel et al., 1996). Today, non-renewable groundwater use and non-sustainable or non-local surface water extraction constitute up to 50 % of the global water consumption (Rost et al., 2008; Wada and Bierkens, 2014).

The increasing demand for freshwater is not only threatening aquatic ecosystems but also human societies. In the year 2000, between 1.5 and 2.5 billion people were living under water scarcity (Liu et al., 2017), measured by a combination of several indicators. This means that the total demand for freshwater cannot always be fulfilled and as a result sometimes there is not even enough water for domestic water use or basic sanitation (Ohlsson and Turton, 2000). Climate change and population growth are expected to further exacerbate this development (Schewe et al., 2014).

Molden (2007) sums up the current dire situation with the following four statements (p. 1):

1. “Competition for scarce water resources in many places is intense”

2. “Many river basins do not have enough water to meet all the demands” (some even fall dry before reaching the sea)

3. “Further appropriation of water for human use is not possible because limits have been reached and in many cases breached”

4. “Basins are effectively ‘closed’, with no possibility of using more water”

In this context additional water withdrawals for bioenergy production seem very problematic. There are no simple solutions to this situation, however it seems clear that better water management in terms of increasing water use efficiency and a better appreciation of water resources could help (Jägermeyr et al., 2016; Rosa et al., 2018).

1.1.3 Greenhouse gas emissions

Human action has also modified the composition of the atmosphere by increasing emissions of greenhouse gases which continuously peak year after year. The two most notable greenhouse gases in terms of global warming potential are carbon dioxide (CO_2) and methane (CH_4). CO_2 emissions mostly stem from fossil fuel use and LULCCs. The dominant CH_4 sources are livestock production, fossil fuel extraction and use, the expansion of rice paddy agriculture and the emissions from landfills and waste (IPCC, 2013). Methane is less stable and converted to CO_2 during a few years. Together with the much higher atmospheric concentrations, this is probably the main reason why negative emissions focus on CO_2. Nevertheless, methane emission avoidance is an important part of mitigation scenarios.

Atmospheric CO_2 concentrations during the glacial period of the past 800,000–12,000 years have periodically fluctuated between 170–300 ppm (Lüthi et al., 2008) and were largely controlled by the Milankovic cycles (Berger, 2001) (Figure 1.2a). During the Holocene, the Earth system was in a stable setting for over 10,000 years (Figure 1.2b). These stable conditions are thought to be an important factor for human development, which in turn led to increasing atmospheric CO_2 concentrations through land-use and fossil fuel emissions. Until 1950, CO_2 emissions were dominated by LULCCs (Houghton et al., 2012), however since then they have been relatively constant. Fossil fuel emissions, about 2 GtC yr^{-1} in 1950, increased almost five-fold until 2015, thereby decreasing the relative share of emissions of LULCCs to about 12.5 % (Friedlingstein et al., 2019). In 1959, Keeling started the longest record of direct atmospheric CO_2 concentrations on Mount Mauna Loa in Hawaii (Tans and Keeling, 2015), which is an important piece of evidence that climate change is man-made (Figure 1.2c). If we look at the sub-yearly values (Figure 1.2d), besides the general trend going up, we can also witness yearly periods which are controlled by the Northern hemispheric seasons. Since a larger portion of the global landmass is located there, carbon uptake and respiration in the Northern hemisphere controls the global trend, which highlights the importance of the biosphere for the carbon cycle.

Today, the biosphere and the oceans behave in favor of stabilizing the climate system. Due to equilibrium processes and increased photosynthesis rates at higher CO_2 levels, only half of the 37 $GtCO_2$

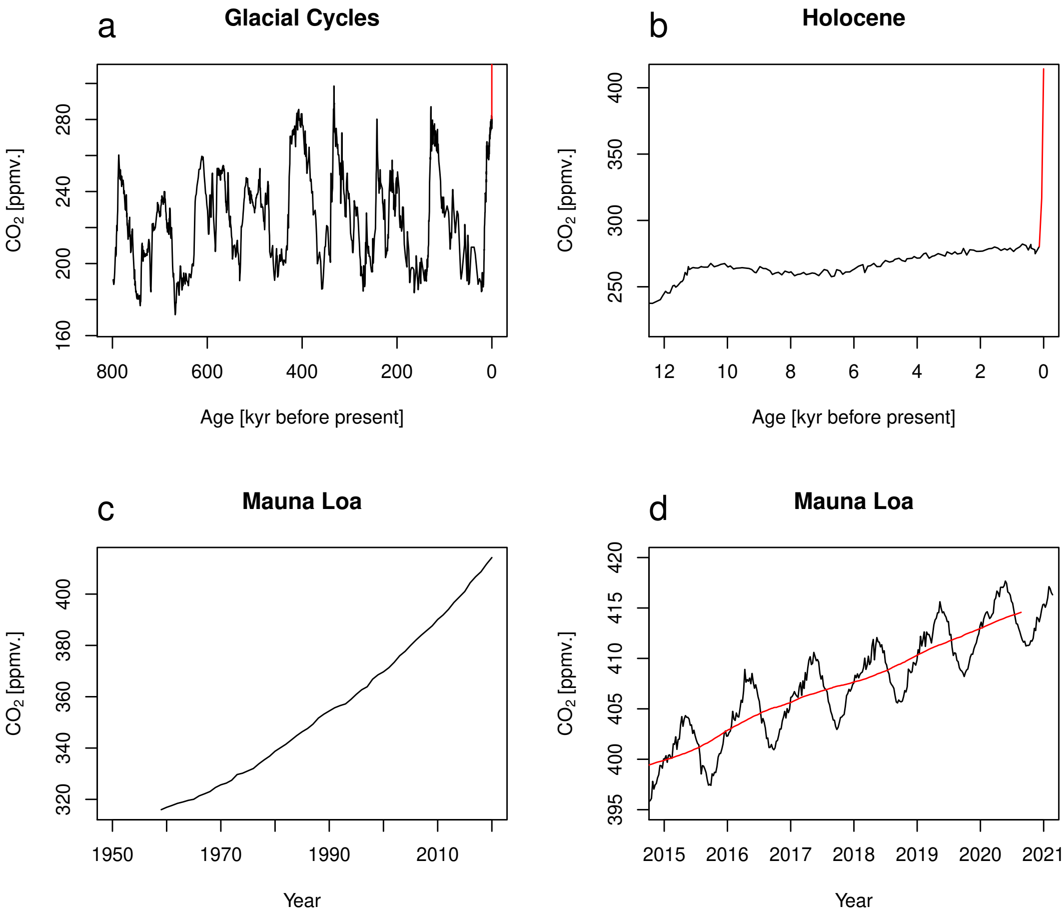


Figure 1.2: Development of atmospheric CO_2 concentrations over time. a Development since Miocene, during ice ages. **b** Stable Holocene period. Both a/b joined with recent Mauna Loa measurement data (red line). **c** Directly measured increase since 1959 (yearly mean values). **d** Directly measured increase since 2015 (weekly data), controlled by yearly carbon cycle with added rolling mean with period=52weeks (red line). Miocene and Holocene values are based on ice core measurements (Lüthi et al., 2008), Mauna Loa direct measurements as published in (Tans and Keeling, 2015).

emitted every year end up in the atmosphere (Le Quéré et al., 2018). In the oceans, CO_2 is dissolving in water and contributing to ocean acidification, while in the biosphere increasing temperatures and CO_2 levels lead to higher biomass productivity. This effect however could reverse in times of decreasing atmospheric CO_2 concentrations (Zickfeld et al., 2016). As a result of reequilibration processes, oceans and biosphere could release some of the previously captured CO_2, which would render even more negative emissions necessary in scenarios already largely relying on negative emissions.

The increasing radiative forcing due to atmospheric greenhouse gases manifests in an increase of local as well as global mean temperature (GMT).

1.2 Climate change induced water stress

The implications of this temperature increase span from sea level rise through melting glaciers and ice sheets over more frequent extreme weather to changing precipitation patterns. In addition, freshwater withdrawals, food production, and now also bioenergy production (to mitigate climate change) will significantly increase the pressure on the biosphere in the coming decades. Today, GMT has increased by about 1 °C above the pre-industrial value (Goddard Institute for Space Studies, NASA, 2021), but scenarios for the 21st century expect an additional 0.5 °C to 5 °C rise until 2100 depending on how humanity acts. A warming of 3 °C would mean that locally the occurrence of extremely hot days becomes much more likely, and length and severity of heat waves will strongly increase, in addition to the aforementioned long-term average effects of climate change (IPCC, 2013).

Water stress, here defined through the local ratio of freshwater demand and supply, already today is higher than 80 % in several large world regions, especially in the subtropics (Alcamo et al., 2003). Climate change will likely exacerbate water stress regionally but also globally (Schewe et al., 2014). However, there are large uncertainties along with regions which potentially benefit from increasing precipitation (Alcamo et al., 2007). The projected shift towards less frequent but more intense precipitation events (Myhre et al., 2019) would mean that less water can be captured by humans or soils, which would effectively reduce water availability. Besides the potentially drastic consequences for humans, this also poses a challenge for global modelling, because the temporal resolution of precipitation inputs can hardly capture these events.

Additionally, basin specific demand changes during the next decades, are largely controlled by population increase, irrigated agriculture, and economic development. They could even have a greater influence on water stress than the changes to natural water availability under climate change (Vörösmarty et al., 2000).

1.3 Negative Emission Technologies

This PhD project was embedded in the CE-Land+ project of the German Research Foundation's (DFG) priority program "Climate Engineering: Risks, Challenges, Opportunities?" (SPP 1689) where the potential for many different technologies to limit climate change and the associated consequences have been analysed and assessed (Löschke and Schröder, 2019).

To limit GMT rise to 2 °C or even 1.5 °C, as required by the Paris Agreement, it is very likely that negative emissions (NEs) are needed, since the emission reduction efforts remain significantly below what would be necessary to reach these goals. NEs are so far only applied to CO_2 emissions, and describe the active large-scale removal of CO_2 from the atmosphere. In some contexts this is also called carbon dioxide removal (CDR) (Bellamy et al., 2012), which can be part of a larger climate engineering (CE) portfolio, also including solar radiation management (SRM) (Keller et al., 2014). SRM will not be discussed in this thesis.

To realize negative emissions, a suite of approaches has been suggested, spanning ocean-based and land-based techniques. An overview is given in the following:

Oceanic CDR (oCDR) is based on increasing the oceanic uptake rate of atmospheric CO_2 by either **increasing ocean alkalinity** through adding limestone powder (Harvey, 2008) or increasing the activity of phytoplankton by **artificial upwelling** of cold nutrient-rich water (Oschlies et al., 2010) or added **iron-fertilizer** (Aumont and Bopp, 2006). The potentials and complex side-effects in the ocean however are not well researched and might include strong termination effects, if the procedure is suddenly stopped (Löschke and Schröder, 2019).

Approaches for terrestrial CDR (tCDR) are more diverse than those for oCDR. The oldest approach is the intentional large scale **afforestation and reforestation** (AR) in suitable areas to accumulate biomass in trees. AR would not require any new technologies, but is limited in its potential by the (relatively) slow growth of trees and the large area requirements (Humpenöder et al., 2014).

Bioenergy with carbon capture and storage (BECCS – the main NET analysed in this study) is based on producing high amounts of biomass with fast-growing woody and herbaceous plant species. The biomass would then be burned for electricity generation or converted to liquid fuels, while the CO_2 would (at least partially) be captured and stored in geologic reservoirs (Gough and Vaughan, 2015). To provide large amounts of NEs, BECCS requires large scale plantation areas, which could compete with food security or efforts of nature restoration to secure biodiversity (Boysen et al., 2017a) and potentially also require irrigation and fertilization (Heck et al., 2016a).

Direct air capture (DAC) is the industrial extraction of CO_2 from the atmosphere with suitable techniques and its subsequent usage (carbon capture usage – DACCU) or storage (DACCS) (Sanz-Pérez et al., 2016). Since there are no additional benefits (like the potential to replace carbon intense coal/gas power plants in the case of BECCS), DAC would, as part of a portfolio of NETs, only be applied at a large scale when an increased carbon price justifies its high costs (Bauer et al., 2018). In contrast to BECCS, DAC might require much smaller areas for similar carbon capture rates. Both BECCS and DACCS rely on a political acceptance of the injection of vast quantities of CO_2 into the ground, which might further limit their potential (Fridahl and Lehtveer, 2018; Gough et al., 2018).

Soil carbon enhancement (SCE) aims at better management of (mainly) agricultural soils and includes better research and management of the effects of irrigation, fertilization, or tillage practices to increase/maintain the soil carbon storage (Minasny et al., 2017). SCE could potentially have a large impact, however its implementation appears difficult, since a large amount of very diverse actors around the globe would have to be involved. SCE can also be understood as an umbrella term for further techniques to boost soil carbon storage, including: **enhanced weathering** (EW) and **pyrogenic carbon capture and storage** (PyCCS). **EW** utilises the weathering of rock powder under consumption of atmospheric CO_2 (Hartmann et al., 2013). It would require a massive mining industry and transport, but could potentially also increase crop yields if applied to agricultural areas. **PyCCS** is based on the pyrolysis of biomass which yields biochar, bio-oil and syngas. The biochar can be applied to arable soils to increase the soil carbon content and can increase crop yields through enhanced water and nutrient holding capacity (Schmidt et al., 2019). PyCCS could thus be a decentralized bottom-up alternative to BECCS, given the availability of the biomass feedstock (Werner et al., 2018).

The detailed analysis in SPP 1689 compared to an initial report by The Royal Society on geoengineering of the climate showed that most of the approaches reveal less potential than initially assumed (Shepherd, 2009; Oschlies and Klepper, 2017).

1.4 BECCS

1.4.1 What is BECCS?

The most prominent NET in ambitious climate scenarios for the 21st century is BECCS (Minx et al., 2018). It relies on the photosynthetic capacity of plants to capture atmospheric CO_2 in biomass, if supplied with enough water, nutrients and light. Large plantations of fast growing plants could thus produce vast amounts of biomass, which would be burned in power plants, or used as the basis for producing biofuels (Carbo et al., 2011; Caldeira et al., 2013). To provide negative emissions instead of a carbon-neutral pathway, the resulting CO_2 from the process needs to be captured and pumped into geologic storages, such as old oil or gas reservoirs (Azar et al., 2006; Lenton, 2010). Thereby the CO_2 would be removed from carbon cycling. An overview of the most prominent conversion pathways for biomass to achieve carbon sequestration together with the maximum carbon conversion efficiencies is given in Figure 1.3.

Suitable plant species have to bridge the gap between maximum yields and robustness for the climate at the plantation site. Depending on temperatures and precipitation, woody plantations of willows, poplars, or *Eucalyptus*, or herbaceous species like *Miscanthus* or switchgrass would be cultivated (Yuan et al., 2008; Woiciechowski et al., 2016). Breeding programs and potentially also genetic modification might further optimize the plant properties, but are likely to be slower than previous productivity increases observed for crops (Searle and Malins, 2014).

1.4.2 Why BECCS is dominating other negative emission technologies

Together with afforestation, BECCS was the first NET to be implemented in integrated assessment models (IAMs) because besides negative emissions, it also provides energy and therefore the potential to offset other carbon-intense energy carriers, such as oil, gas and coal (Klein et al., 2014).

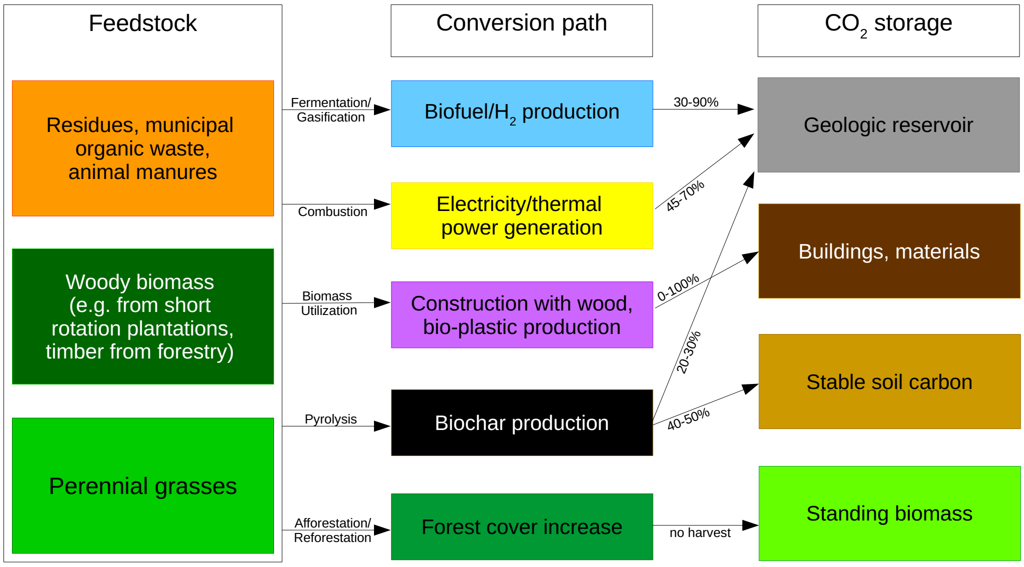


Figure 1.3: Overview of the biomass process chain to achieve carbon sequestration from feedstock production to final storage. The arrow labels between Feedstock and Conversion path denote the biomass conversion process, those between Conversion path and CO_2 storage give the associated maximum carbon conversion efficiency (overall percentage of harvested carbon that is permanently removed from carbon cycling). The remaining fraction will eventually go back into the atmosphere. BECCS is usually considered along pathways of electricity/thermal power generation or biofuel/H_2 production. Based on Lenton (2010); Smith and Torn (2013); Luderer et al. (2015); Rossi et al. (2015); Werner et al. (2018); Fajardy et al. (2019); Bals et al. (2019)

High discount rates reinforce this dependence on BECCS in IAMs, because investments in renewable energy technologies are postponed to the second half of the 21st century and alternative NETs are missing (Köberle, 2019). Instead, co-benefits or trade-offs with other NETs and an associated monetary value for the required ecosystems services (water demand and land-use potentially resulting in biodiversity loss) would lead to completely different scenarios. Already today, there are alternative 1.5 °C compatible scenarios without large scale BECCS use (Meinshausen and Dooley, 2019). However, they entail other challenges such as quickly ramping up renewables to phase out coal and gas or monitoring and management of natural carbon sinks instead of CCS.

1.4.3 Potential of BECCS

Theoretically, BECCS could provide more than 5 GtC yr^{-1} (18 $GtCO_2$ yr^{-1}), or 200 EJ yr^{-1}, given that areas of more than 500 Mha would be converted to biomass plantations (see chapter 3 and Bonsch et al. 2016; Heck et al. 2016b, 2018; Hejazi et al. 2014; Jans et al. 2018 discussed therein). In the IPCCs AR5 (IPCC, 2015), a large fraction of the scenarios limiting global warming to below 2 °C require vast amounts of bioenergy, most of them combined with CCS (Figure 1.4).

There is consensus within the scientific community that future crop production should not be affected by bioenergy production. As a result, other areas would have to be utilised. Indirect or unwanted competition with crops might however still evolve if market forces alone would control the bioenergy development. The remaining natural land, when cropland is excluded, sums up to almost 7,000 Mha (Boysen et al., 2017b). In a simulation study (chapter 4), I find that sparing at least all currently protected reserves and areas of conservation interest would more than halve this *potentially available area for biomass plantations* to roughly 3,300 Mha. Within these areas, there are locations where the average biomass plant could not be economically grown (at least 2.5 t C ha^{-1} yr^{-1}) or where biomass harvests would not compensate for the high land-use change emissions. Taking this into account would further reduce the area to 1,000–1,400 Mha. With substantial irrigation and more efficient BECCS processes, NEs of more than 300 GtC could be accumulated on these areas over the century (chapter 4). Biomass production on marginal (crop) land might contribute 385–472 Mha (with partial overlap) and could also contribute to soil restoration (Campbell et al., 2008).

1.4.4 Side effects of BECCS

Utilization of fast-growing plants sounds like a "green" solution to limiting climate change. To provide substantial NEs however, bioenergy plantations (BPs) would require large amounts of land, water for irrigation, and potentially also fertilization. Resulting negative impacts include increased competition with the food producing agriculture, water pollution, accelerated biodiversity loss, or increased water scarcity (Heck et al., 2016a; Boysen et al., 2017a; Yamagata et al., 2018). A set of further side-effects stem from biomass processing, especially the CCS part required to provide negative emissions. Transport of biomass or CO_2 requires large scale infrastructure, while the CCS process and the repository itself entail risks of environmental pollution and CO_2 leakage, dangerous for humans and animals (Damen et al., 2006). These risks may also impact the public acceptance of the CCS technology, which could lower the overall potential (Fridahl and Lehtveer, 2018).

In particular the effects of biomass plantations on freshwater availability, in relation to the substantial pressure from water use for agriculture, industries, households, have hardly been assessed so far and are the subject of this thesis.

1.4.5 Why BECCS is likely to be irrigated

The biomass production will likely be a decentralized effort in which many actors will be involved. In general, crop farmers are looking to increase the per hectare productivity in order to maximize profits, which will also be true for biomass plantations. Because there is limited land available, minimizing the required land for bioenergy is also relevant from a political-administrative viewpoint because of the

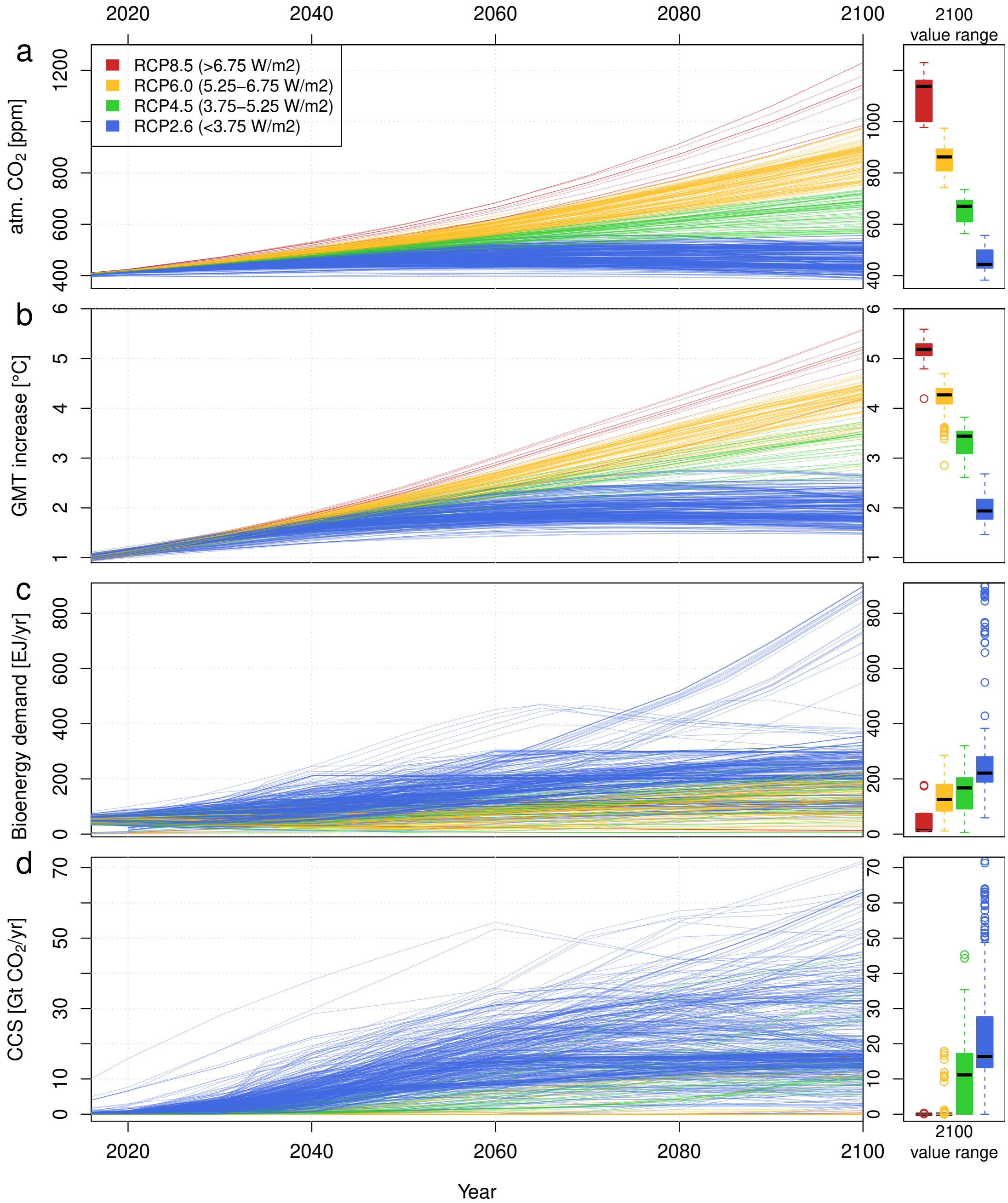


Figure 1.4: Atmospheric CO_2, GMT increase, Bioenergy and CCS demand based on IPCC AR5 scenarios, available from the PIK AR5 scenario explorer (IPCC, 2015). Scenarios are color-coded according to the radiative forcing in 2100. Panels on the left show the yearly values for atmospheric CO_2 content, GMT increase compared to preindustrial, Bioenergy demand and CCS. Panels on the right show the 2100 value range for each RCP group.

potential competition with producing enough food to feed the population (Searchinger and Heimlich, 2015; Gerten et al., 2020). Looking at the projected population growth, this might be a problem of its own. Currently, most scenarios of future development include only rainfed biomass plantations, however the aforementioned incentives to maximize the productivity will likely put irrigation on the plan (Bonsch et al., 2016). A substantial carbon price, which would also be reversely applicable to negative emissions ("credits for sequestration"), might further amplify this, and also compensate for the required additional investment in irrigation systems (Hogan et al., 2007; Bauer et al., 2018).

In conclusion, it seems likely that there will be irrigation for biomass production in the future, however to what extend and under which political regulations remains uncertain. A better understanding of the drivers of historic irrigation expansion on cropland might also help to predict more reliably how the water demand for biomass plantations will develop in the future.

Substantial additional freshwater withdrawals for biomass production in the order of up to 5,000 $km^3\ yr^{-1}$, as suggested by several previous studies (Beringer et al., 2011; Hejazi et al., 2014; Bonsch et al., 2016; Heck et al., 2016b; Yamagata et al., 2018), could however further increase water stress, which in many regions is already high today (Schewe et al., 2014). This also highlights the dilemma that water stress is likely to increase in the future, either through climate change or climate change mitigation measures such as BECCS. In chapter 5, I analyse this in more detail, with sustainable water management as a potential way out of the dilemma.

1.4.6 Implementation gap

Using second-generation (lignocellulosic) bioenergy plants for BECCS to provide NEs is a relatively young idea compared to first-generation bioethanol production from oil-crops (Laude et al., 2011). Currently, the deployment status is still in the research and testing phase (Fajardy et al., 2019; Gough and Mander, 2019). This is especially the case for the technologies required for CCS, which today are mostly used in conjunction with fossil fuel power plants for enhanced oil recovery (Page et al., 2020). Large scale field studies for the whole BECCS process chain are missing so far. This might be due to a lack in financial investment interests, which highlights a large BECCS implementation gap (Fuss and Johnsson, 2021). Experimental field data is only available for biomass growth parameters. Therefore almost all insights for the entire BECCS process chain are based on highly stylized value chain models and projections of future socio-economic and land-use development provided by complex global models (Klein et al., 2014; Fajardy and Mac Dowell, 2017).

1.5 Research outline

While BECCS is primarily designed to provide NEs, this thesis analyses the associated side-effects regarding freshwater availability and use. Potentially large quantities of irrigation water are required for carbon dioxide removal via biomass plantations and the resulting water stress motivate the research agenda. In an initial literature review, I analyse the projected global irrigation water demand for biomass plantations (P1 – chapter 3) and present an overview of methods and approaches, as well as modelling parameters used by the various authors. On this basis, I systematically model the irrigation water demand required to reach the 1.5 °C target (P2 – chapter 4) in a set of comprehensive simulations, including scenarios of sustainable water management. Finally I compare the end-of-century water stress between a strong climate change scenario and a climate mitigation scenario using irrigated BECCS to illustrate the ambiguous effects (P3 – chapter 5). The three chapters cover the following key questions:

P1 - Which key modelling assumptions and parameters control the projected global freshwater demand for irrigation of bioenergy plantations?
In this study, I review existing global assessments of freshwater requirements for bioenergy production. The result is a comprehensive database, which illustrates the diverse assumptions made in the literature. To compare water productivity, I calculate the freshwater amount required per ton of biomass harvest. For future studies I conclude that full disclosure of the parameters is crucial to interpreting and comparing reported estimates of possible future bioenergy water use. Further, water demands for bioenergy and the trade-offs that might go along with them should be an integral part of global assessments of freshwater demand and use.

P2 - What is the potential of optimal bioenergy plantation locations and sustainable water management for achieving the 1.5 °C target?
This study provides a first-order quantification of the biophysical potentials of BECCS as a negative emission technology contribution to reaching the 1.5 °C target, constrained by associated water availability and requirements. The simultaneous water demands for agriculture, industries, and households are taken into account, as well as environmental flow requirements (EFRs) needed to safeguard aquatic ecosystems. Furthermore, I assess with several scenario sets to what extent different forms of improved water management on the suggested BPs and on cropland may reduce the freshwater abstractions or reach the otherwise unattainable sequestration goal.

P3 - Do irrigated bioenergy plantations have a larger effect on water stress than the avoided climate change?
In this synthesis study, I compare future water stress in a high temperature world with a mitigation

scenario based on large scale irrigated bioenergy plantations to illustrate the water stress dilemma humanity is facing. As a potential way out, I include a scenario with strict water policies. In the scenario, environmental flow protection is combined with advanced on-field water management, to show under which conditions BECCS can provide substantial negative emissions without leading to water stress. The simulations are based on fully consistent scenario data from the ISIMIP2b protocol, which provides pathways to 1.5 °C requiring substantial bioenergy use (RCP2.6) and 3 °C (RCP6.0).

All three studies (P1, P2, and P3) are published in peer-reviewed, ISI-listed journals. Answers to the research questions are provided in chapter 6.

2
Methods

This chapter provides an overview of the scenarios, the LPJmL model, further modelling assumptions and input datasets used in the projects of this PhD thesis.

2.1 Scenario assumptions

In order to provide socio-economic narratives as a framework for potential future development, the shared socioeconomic pathways (SSPs) were developed (Kriegler et al., 2014; O'Neill et al., 2014; Van Vuuren et al., 2014). They provide trends until the end of the 21st century. The SSPs are:

- SSP1: Sustainability (Taking the Green Road)
- SSP2: Middle of the Road
- SSP3: Regional Rivalry (A Rocky Road)
- SSP4: Inequality (A Road divided)
- SSP5: Fossil-fueled Development (Taking the Highway)

Each of these storylines comes with trajectories of population, urbanization, and gross domestic product (GDP) development. Those can be fed into IAMs to evaluate what would be necessary to achieve a certain climate trajectory. In the ISIMIP2b project (from which scenarios are used in chapter 5) SSP2 is used, as it is compatible with both high climate change and strong climate mitigation pathways.

In order to assess the likelihood of achieving certain climate change trajectories and their effects on e.g. ecosystems or human development, a set of representative concentration pathways (RCPs) for atmospheric greenhouse gases (given in CO_2 equivalents) was developed. They form the basis of the Coupled Model Intercomparison Project Phase 5 (CMIP5 – Taylor et al. 2012) for the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC 2013). The RCPs are named after the resulting radiative forcing from the atmospheric greenhouse gases in the year 2100. The AR5 contains four RCPs (RCP2.6, RCP4.5, RCP6.0, and RCP8.5), to which CMIP6 is adding three more steps (RCP1.9, RCP3.4 and RCP7.0 – Eyring et al. 2016). The lower the targeted radiative forcing in 2100, the higher is the required bioenergy share of the primary energy demand and the negative emissions (CCS) in order to stay on these paths. In the scenario assessments for the IPCC AR5 (which are the basis for my modelling studies), the 2100 median bioenergy demand for RCP2.6 scenarios exceeds 200 EJ yr^{-1}, the median amount of CCS is about 17 $GtCO_2$ yr^{-1} (Figure 1.4). These high numbers (and the required strong ramp-up during this century) motivate looking into the water demand of this large scale negative emission endeavour. Consequentially it prompts a comparison of the resulting water stress with an alternative pathway without BECCS and more severe climate change.

2.1.1 Input datasets for modelling

Using the RCPs as forcing data, General Circulation Models (GCMs) can evaluate the resulting global fields of temperature, wind, or precipitation (Giorgetta et al., 2013). These data can then be used for complex integrated assessment models, which are based on a combination of economic and ecological modules. Land-system models provide potential yields and water demands (Schaphoff et al., 2018b), which can be input to agro-economic models to assess the feasibility to achieve a certain RCP-SSP combination. As a result, they can show which sets of negative emissions demands, land-use patterns, or technological investments would be needed (Dietrich et al., 2019). In chapter 4 I start with yearly negative emission demands required to limit GMT increase to 1.5 °C to create a set of land-use scenarios optimized for high water-use-efficiency on BPs around current agricultural and protected areas.

The ISIMIP framework compares the impacts of global warming and requirements for its limitation between several models and sectors and provides a unique set of consistent input data. In the case of ISIMIP2b (Frieler et al., 2017) relevant inputs for this dissertation are climate, land-use, water-use, and population trajectories until 2100, based on SSP2. In chapter 5, I utilize these inputs to assess what the water stress, resulting from irrigation of bioenergy plantations, would be to provide the required negative emissions to meet RCP2.6 and compare it to the water stress in RCP6.0.

2.2 LPJmL model

The interactions between climate change mitigation and the associated freshwater demand for irrigation of bioenergy plantations can be simulated using the dynamic global vegetation model LPJmL (Schaphoff et al., 2018b), developed and maintained at the Potsdam Institute for Climate Impact Research (PIK). LPJmL simulates biophysical processes of the natural biosphere, grasslands, and 12 crop functional types plus a group of other annual and perennial crops based on prescribed land-use patterns (Bondeau et al., 2007). For that purpose, the global land area is divided into 67,420 cells from a $0.5° \times 0.5°$ global grid. In each cell, daily carbon and water dynamics are simulated based on soil and climatic conditions (including atmospheric CO_2). Sowing dates can be dynamically calculated (Waha et al., 2012) and calibrated to match national yield statistics (Fader et al., 2010). The model also includes woody and herbaceous second generation bioenergy crops, parametrised as temperate willows and poplars, tropical *Eucalyptus*, or *Miscanthus* and switchgrass (Beringer et al., 2011; Heck et al., 2016b; Boysen et al., 2017b). The bioenergy yields were evaluated against field data (Heck et al., 2016a).

Crops and biomass plantations can be rainfed or irrigated based on three irrigation systems: surface, sprinkler and drip (Jägermeyr et al., 2015). Additionally, water management strategies, like mulching, local water storage and conservation tillage can be applied (Jägermeyr et al., 2016). The blue and green water fluxes between cells are based on local water availability and discharge, which is routed through a river network with dams and reservoirs (Gerten et al., 2004; Rost et al., 2008; Biemans et al., 2011). Domestic, industrial, as well as livestock water withdrawal and consumption are included as an additional external water use input. Irrigation can be constrained by surface water availability, or alternatively by a strict global water policy limiting the irrigation water withdrawals according to EFRs (Jägermeyr et al., 2017).

2.2.1 Sustainable water management

In recognition of the importance of natural flow regimes for healthy river ecosystems as well as human well-being, the concept of environmental flows (EFs) has been established (Poff et al., 1997). The *Brisbane Declaration on Environmental Flows* defines it as "the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems" (Brisbane Declaration, 2007). Most of the subsequent analyses based on this approach define volumes or water levels very specific to the river or river basin of interest (Arthington et al., 2018). However, there are also global approaches for EF appropriation (Postel et al., 1996), which define methods to calculate EFRs from monthly river flow (Pastor et al., 2014). Most of them are based on hydrological or land-use models. These methods are less suitable for specific river systems, but provide the opportunity to integrate EF provision as a global policy option or assess the current situation in a large set of basins at once with the same approach.

For my studies I have applied an LPJmL module developed by Jägermeyr et al. (2017) and used the variable monthly flow (VMF) method (Pastor et al., 2014) to calculate EFRs based on mean monthly discharges of the last undisturbed period of 1670–1699. Months are classified into either a low, medium or high-flow season, in which 60 %, 45 %, or 30 % of the pristine local discharge is allocated to riverine ecosystems and cannot be withdrawn in future years. The flow season of a given month is defined compared to the mean annual flow. Intermediate-flow months are defined by a mean monthly flow (MMF) below 80 % and above 40 % of the mean annual flow (MAF), low flow months below, and high-flow months above this range (Figure 2.1).

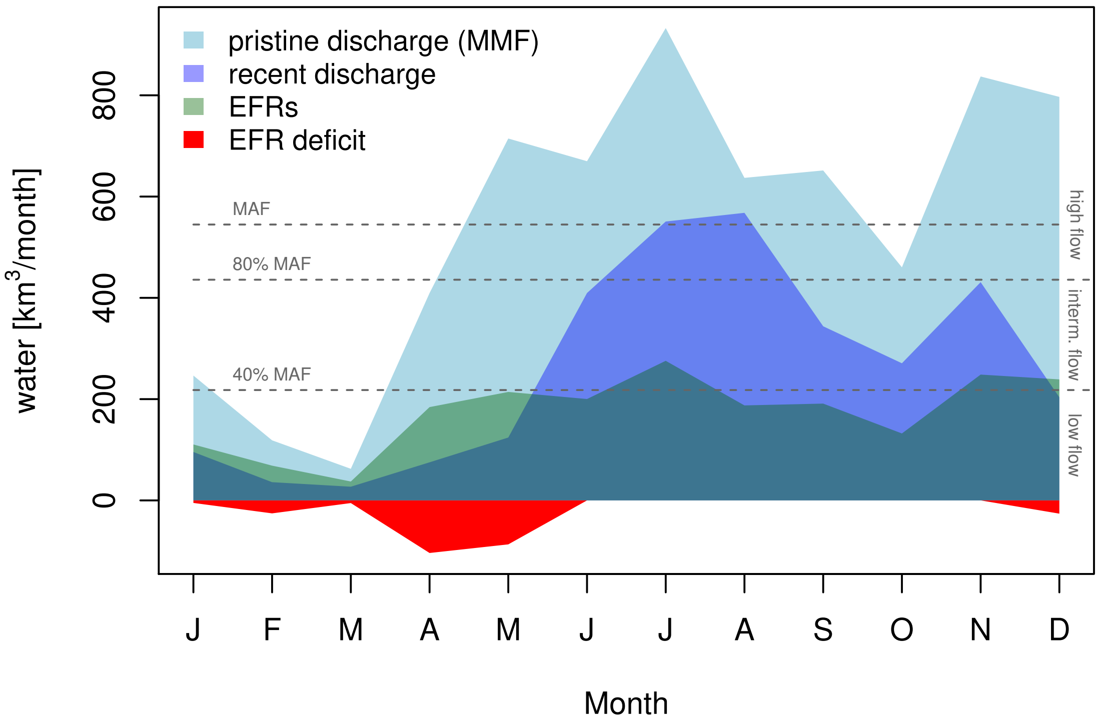


Figure 2.1: Environmental flow requirements (EFRs) based on pristine discharge (mean 1670-1699) calculated with the VMF method for an exemplary LPJmL cell (10.25, -62.75). February and March are classified as low flow months (EFR: 60 % of MMF). January and April are classified as intermediate flow months (EFR: 45 % of MMF). The remaining months are classified as high flow months (EFR: 30 % of MMF). EFR deficit is displayed when recent discharge (mean 1996-2005) cannot fulfil EFRs.
MAF: mean annual flow; MMF: mean monthly flow; VMF: variable monthly flow

Providing sufficient food for a growing population poses one of the major challenges for humanity in the coming decades (Jägermeyr, 2020). One key factor to achieve this could be the intensification of sustainable farm-level water management practices to increase yields. The proposed methods focus on local storage of rainwater and retaining soil moisture through mulching and conservation tillage in order to bridge dry spells (Rockström and Falkenmark, 2015). The practices were proposed for Africa, however also farmers in other world regions could benefit greatly from implementing such practices (Jägermeyr et al., 2016). A set of water management options has been incorporated into LPJmL by Jägermeyr et al. (2016) and can also be applied to biomass plantations to buffer the yield decline through EF protection and thereby creating a more sustainable system.

I combine the restriction of freshwater withdrawals according to EFRs with farm level water management practices to receive a *Sustainable Water Management* practice scenario (called WM in chapter 4, SWM in chapter 5). This serves as a global water policy in which the environmental water demand is recognized as globally important and therefore freshwater withdrawal quotas are implemented. To account for the reduced irrigation water availability, at the same time, on-field water use efficiencies are improved.

3
Global scenarios of irrigation water abstractions for bioenergy production: a systematic review

An edited version of this chapter has been published in the journal Hydrology and Earth System Sciences Discussions:

Stenzel, F., D. Gerten, and N. Hanasaki. Global scenarios of irrigation water abstractions for bioenergy production: a systematic review. *Hydrology and Earth System Sciences*, 25(4):1711–1726, 2021a.
https://doi.org/10.5194/hess-25-1711-2021

3.1 Abstract

Many scenarios of future climate evolution and its anthropogenic drivers include considerable amounts of bioenergy as fuel source, negative emission technology, and for providing electricity. The associated freshwater abstractions for irrigation of dedicated biomass plantations might be substantial and therefore potentially increase water limitation and stress in affected regions; however, assumptions and quantities of water use provided in the literature vary strongly. This paper reviews existing global assessments of freshwater abstractions for bioenergy production and puts these estimates into the context of scenarios of other water use sectors. We scanned the available literature and (out of 430 initial hits) found 16 publications (partly including several scenarios) with reported values on global irrigation water abstractions for biomass plantations, suggesting water withdrawals in the range of 128.4–9,000 $km^3\ yr^{-1}$, which would come on top of (or compete with) agricultural, industrial, and domestic water withdrawals. To provide an understanding of the origins of this large range, we present the diverse underlying assumptions, discuss major study differences, and calculate an inverse water use efficiency (iwue) which facilitates comparison of the required freshwater amounts per produced biomass harvest. We conclude that due to the potentially high water demands and the trade-offs that might go along with them, bioenergy should be an integral part of global assessments of freshwater demand and use. For interpreting and comparing reported estimates of possible future bioenergy water abstractions, full disclosure of parameters and assumptions is crucial. A minimum set should include the complete water balances of bioenergy production systems (including partitioning of blue and green water), bioenergy crop species and associated water use efficiencies, rainfed and irrigated bioenergy plantation locations (including total area and meteorological conditions), and total biomass harvest amounts. In the future, a model intercomparison project with standardized parameters and scenarios would be helpful.

3.2 Introduction

Previous assessments of global green and blue water requirements of a potential widespread bioenergy industry show a large variation in the estimates (withdrawals of 128.4–9,000 $km^3\ yr^{-1}$ – De Fraiture et al. 2008; Hejazi et al. 2014), while there is still insufficient analysis of the underlying sources of variation and assumptions, that need to be standardized.

Projections of future energy demand and its partitioning increasingly assume replacement of carbon-intense fossil energy carriers with biomass, which could provide carbon-neutral electricity or fuels (Nakićenović et al., 1998; Rose et al., 2014; Bauer et al., 2018). However, in order to limit mean global warming to 2 °C or even 1.5 °C (UNFCCC, 2015), technologies providing additional negative emissions (NEs) are potentially needed to compensate for residual and past emissions (Rockström et al., 2017; Minx et al., 2018; Rogelj et al., 2018). One such NE technology (NET) is bioenergy with carbon capture and storage (BECCS). Bioenergy utilizes plant photosynthetic capacity to make available energy from sunlight in biomass, whereby CO_2 is extracted from the atmosphere but at the same time water is transferred from soil to the atmosphere in the process of evapotranspiration. Due to the large amount of potentially needed NEs in the second half of the century (e.g. 3.3 GtC yr^{-1}, Smith et al. 2016; 2–5 GtC yr^{-1}, Rogelj et al. 2015), the feedstock is projected to be grown on large managed plantations and include substantial irrigation, demanding trade-offs between negative emissions and area requirements as well as water consumption to be solved sustainably.

Suggested energy carriers for BECCS are either energy-rich plant organs (e.g. rapeseed, oil palms, sugar cane) to be directly converted to biofuels (first-generation bioenergy) or lignocellulosic biomass from fast-growing plants such as maize, *Miscanthus*, switchgrass, willows or *Eucalyptus* (Yuan et al., 2008; Woiciechowski et al., 2016), i.e. second-generation bioenergy. These diverse plants have different growth rates, preferred climatic zones, and also – depending on the location where they are projected to be grown – different freshwater demands (King et al., 2013).

While burning of fossil energy carriers leads to (net positive) emissions of greenhouse gases, use of biomass is net neutral apart from land-use and process-chain emissions (Al-Ansari et al., 2017). Thus, use of bioenergy can offset other carbon-intensive means of energy generation, such as coal, gas, or oil (Gough et al., 2018; Fajardy and Mac Dowell, 2017). To provide respective NEs, bioenergy use needs to be complemented by means of carbon storage. Proposed methods include pyrogenic carbon capture and storage (PyCCS - Werner et al. 2018; Schmidt et al. 2019), BECCS (Azar et al. 2006; Lenton 2010), or other long-term storage preventing a release of the captured carbon back to the atmosphere. For a comprehensive analysis of carbon capture technologies, see for example Markewitz et al. (2012).

Bioenergy plantations (BPs) can be either completely rainfed or partially irrigated. Plantations of the former type would completely depend on ”green” precipitation water stored in soils, while the latter additionally include more or less pronounced use of ”blue” water from lakes, rivers, reservoirs and aquifers (Hoekstra et al., 2009; Fader et al., 2011; Wang et al., 2017).

The discussion for or against large scale irrigation of BPs revolves around a set of economic and sustainability trade-offs, requiring a more comprehensive quantification of water use of bioenergy systems. The required high biomass productivity for reaching ambitious climate targets might promote irrigation to reduce land requirement trade-offs with e.g. food production. This however would happen at the expense of freshwater ecosystems (Poff and Zimmerman, 2010) and human societies in terms of increased overall water stress (Schewe et al., 2014), or lead to unwanted modification of terrestrial water cycling (Vervoort et al., 2009). Additional investment in irrigation systems would be required (Hogan et al., 2007), which however might become economically feasible due to an increased value of biomass through carbon pricing (Bauer et al., 2018). Li et al. (2018) report at least 15 % (and potentially much more due to most studies not reporting this parameter) of field experiments with lignocellulosic bioenergy crops to be irrigated.

Additionally, the process chain from biomass to NEs requires water as well, but has rarely been quantified (e.g. in Smith et al. 2016). This might be because large-scale CCS is not yet in place and the process of conversion to energy and subsequent long-term storage is usually not modelled in detail by the existing models. One exception is Fajardy et al. 2018, who also include polluted ("grey") water from the biomass processing chain.

Review studies on the potentials of BECCS and other NE technologies (e.g. Creutzig et al. (2015), Smith et al. (2016) and Fuss et al. (2018)), have so far not provided a comprehensive overview of the associated freshwater abstractions (besides their precursory mentioning).

The suggested large quantities of blue water withdrawals/consumptions assumed for BP irrigation in the literature, which may occur in competition with other water uses and may increase water stress in relatively water-scarce regions where BPs are considered, motivate a comprehensive understanding and quantification of their intrinsic water requirements (Hejazi et al., 2015; Wada et al., 2014). Thus, the subject of the present paper is to fill this knowledge gap and systematically review the current literature on projected freshwater abstractions in global NE or energy scenarios relying on BECCS/bioenergy. Additionally, we illustrate how such global scale syntheses could be standardized in data requirements/formats, analytical framework, scopes of inference, supporting assumptions, and reconciliation across spatio-temporal scales.

The analysis is guided by the following questions:

1. What are the key modelling parameters and assumptions of global bioenergy studies that affect the inherent water demand projections? (section 3.4.1 and section 3.4.2)
2. What are the global freshwater abstractions for irrigation of bioenergy plantations in the future as projected in available global-scale studies? (section 3.4.3)
3. How do amounts of freshwater abstractions for irrigated biomass plantations compare to other sectors? (section 3.4.4)
4. Is there a dependence between the simulated freshwater abstractions and the total global biomass production across studies? (section 3.4.5)

The resulting literature corpus consists of 16 publications containing a total of 34 scenarios. In principle one could also include local or regional studies, but their numbers cannot be straightforwardly up-scaled or compared with the global studies due to a lack of site specific data for plantation locations in global studies. We separate quantities of blue water application on BPs into withdrawals (gross extraction from rivers, lakes, reservoirs) or consumption (eventual evapotranspiration, excluding return flows to the rivers and water bodies that may occur after withdrawal). Existing studies are then compared regarding a) the total global water volume quantified as a component of the hydrological cycle, and b) the global mean water use efficiency per biomass produced (iwue – water abstractions per biomass produced, see Equation 3.1) inferred from the studies as a component of field-scale water management.

3.3 Methods

3.3.1 Literature search query

We scanned the WebOfScience, as well as the SCOPUS database on February 05, 2020 with a query covering all global BECCS and bioenergy studies that mention use, consumption, withdrawal, or demand of water in their abstract, keywords, or title and excluded studies which focused on algae or electrofuels:

```
("BECCS" OR "bioenergy production" OR "bioenergy cultivation" OR "biomass
production" OR "biomass plantation*") AND (( "water" AND ("use" OR "demand"
OR "consumption" OR "withdrawal")) OR "irrigation") AND ("global") NOT
("algae" OR "algal" OR "electrofuels")
```

From the resulting 430 studies, we removed all those which did not deal with BPs or BECCS at all, had only a regional scope, or only gave qualitative estimates of the freshwater abstractions of large-scale BPs (going from title to abstract to full text). The global bioenergy studies with water consumption values by King et al. (2013); Smith et al. (2016); Smith and Torn (2013); Varis (2007); Séférian et al. (2018) were included as supplementary ”green water studies” in our corpus, because they did not consider irrigation, but only rainfed biomass plantations (and CCS process water in the case of Séférian et al. 2018). We manually added the study by Hejazi et al. (2014) which did not show up in the systematic query described above. The resulting total of 16 ”blue water” publications (+ 5 ”green water”) together with the main parameters are listed in Table 3.1. Noticeably, the majority of publications are very recent – only two of them were published before 2010.

3.3.2 Calculating an inverse water use efficiency (IWUE)

Comparison of the literature values of water abstractions for BECCS is not straightforward because of the different assumptions studies made on important model parameters and setups, as described in section 3.4.2. Nevertheless, besides presenting the absolute global estimates of freshwater withdrawal or consumption, we attempt to make the results of these studies directly comparable: The degree of assumed bioenergy deployment varies strongly among studies, we thus relate the given freshwater abstractions to the absolute amount of biomass assumed to be grown. With this we quantify the estimated water abstractions per harvested biomass. King et al. (2013) compute a similar “bioenergy

Table 3.1: List of publications with published key bioenergy parameters analysed in this review. See supplementary dataset (Stenzel et al., 2021c) for additional parameters and all scenarios per study.

Author	Year publ.	Area [Mha]	Energy [EJ/yr]	NE [GtC/yr]	Year (scen.)	water abstr. [km^3/yr]	water process[§]	c_eff[+] [%]
blue water studies								
Beringer et al.	2011	142–454	52–174	-	2050	1,481–3,880	cons	-
Berndes	2002	-	304	-	2100	2,281	cons	-
Bonsch et al.*	2016	468–740	300	-	2100	3,362–5,860	wd	31–43
Boysen et al.*	2017	441	-	-	2100	125–2,536	cons	50
Fajardy et al.	2018	930	-	3.3	2016	5,700	cons	33
De Fraiture et al.	2008	42.2	-	-	2030	128.4	wd	-
Gerbens-Leenes et al.	2012	-	71	-	2030	466	cons	-
Heck et al.*	2016	1,500	-	-	2005	1,344–1,501	cons	-
Heck et al.*	2018	778–870	151–233	1.2–5.4	2050	1,525	cons	48–90
Hejazi et al.*	2014	596–8,195	40–140	0–10	2095	1,000–9,000	wd	94
Hu et al.*	2020	431	-	3.1	2100	2,260–11,350	cons	36–72
Humpenöder et al.	2018	636	300	-	2100	973–1,211	cons	-
Jans et al.*	2018	400–4,300	200–2,350	-	2015	1,300–9,000	cons	-
Mouratiadou et al.	2016	511	400	-	2100	2,700	wd	-
Stenzel et al.*	2019	1,072–1,416	-	4.4–8.9	2100	351–2,946	cons	50–70
Yamagata et al.	2018	250	-	2.9	2095	1,910	cons	33
green water studies								
King et al.	2013	363–493	33–47	-	2050	1,000	cons	-
Séférian et al.	2018	-	220–270	-	2100	178	cons	-
Smith and Torn	2013	218–990	-	1.0	2100	1,600–7,400	cons	47
Smith et al.	2016	100–200	-	3.3	2100	720	cons	100
Varis	2007	-	83.52	-	2050	2,088	cons	-

* parameter ranges span several scenarios
§ consumption (cons), withdrawal (wd)
+ carbon conversion efficiency

water use efficiency at the farm gate" for several lignocellulosic bioenergy species based on the yield of (bio)energy per hectare per water volume evapotranspired. We extend this concept of local level water use efficiency to larger spatio-temporal scale and apply it as an inverse (global) water use efficiency (iwue):

$$iwue \left[\frac{\mathrm{km}^3}{\mathrm{GtC}}\right] = \frac{water\ \left[\mathrm{km}^3\right]}{biomass\ harvest\ [\mathrm{GtC}]} \tag{3.1}$$

For the analysis, we separate the scenarios into those that report water withdrawals or consumption per energy unit supplied from bioenergy ("energy studies") and those that report NEs along with estimates of related withdrawals or consumption ("NE studies"). From the energy studies, we backtrack the approximate dry biomass harvests by using the gross calorific value of 18.5 MJ kg^{-1} DM (Haberl et al., 2010; Brosse et al., 2012). This is equivalent to 37 MJ kgC^{-1} or 37 EJ GtC^{-1}, with the average carbon content of dry biomass of 0.5 kgC kg DM^{-1} (Schlesinger and Bernhardt, 1991, p.120) (Equation 3.2).

$$\textit{biomass harvest}_{\textit{from energy}}\ [\mathrm{GtC}] = \frac{\textit{energy}\ [\mathrm{EJ}]}{37\ \mathrm{EJ\ GtC}^{-1}} \tag{3.2}$$

With this we approximate the initial biomass harvest from the reported bioenergy supply, however neglecting losses during processing, if they were considered. Note that using one value for carbon content of biomass is an oversimplification, naturally the value depends on the bioenergy crop type (Ma et al., 2018). Therefore, for ideal comparability not only the feedstock type, but also the harvest shares would need to be reported. For NE studies that document an assumed carbon conversion efficiency (c_{eff} – the fraction of carbon from biomass harvest that is eventually sequestered and removed from carbon cycling), we derive the dry biomass harvest by division of the NE amount by c_{eff} (Equation 3.3). Since transport and other losses are usually contained in c_{eff}, the inferred initial biomass values for NE studies are probably more reliable than those for energy studies.

$$\textit{biomass harvest}_{\textit{from NE}}\ [\mathrm{GtC}] = \frac{\textit{NE}\ [\mathrm{GtC}]}{c_{\textit{eff}}} \tag{3.3}$$

Some studies assume also the use of residues from agriculture and forestry (Beringer et al., 2011; Fajardy et al., 2018), timber harvest from land-use conversion (Heck et al., 2018; Stenzel et al., 2019), municipal solid waste, or animal manures (Beringer et al., 2011) as bioenergy feedstock. Respective amounts, however, are only reported in Beringer et al. (2011). We may therefore overestimate the raw bioenergy harvests or conversely underestimate the water abstractions per unit of biomass from dedicated BPs.

3.4 Results and Discussion

3.4.1 Overview

We synthesize the results from the 16 publications into 34 scenarios of freshwater abstractions for bioenergy (the full data-set is available as Stenzel et al. 2021c). As freshwater abstractions, we extract reported estimates of blue water consumption or withdrawals, with a preference on consumption.

Modelling approaches used are very different, with each model focusing on a different part of the BECCS deployment process. While Earth System Models (ESMs) dynamically represent large-scale feedbacks between atmosphere, ocean and biosphere with comparably less process detail regarding human management of the biosphere including BPs, integrated assessment models (IAMs) focus on future developments of e.g. land and water use based on biophysical and economic boundary conditions – explicitly accounting for decisions on BP locations and resource use. In contrast, climate or land-use patterns are typically prescribed to crop/vegetation and hydrological models, which in turn usually operate at higher spatio-temporal resolution and provide more process-based interactions, especially regarding the simulation of water availability and withdrawal. If deriving global estimates of BP freshwater withdrawal or consumption is an aim of a study, more straightforward and computationally inexpensive estimations might suffice. Value chain models might be best suited if the details of the BECCS process chain are of most interest.

The natural water availability in bioenergy modelling studies is largely determined by the considered climate input, which in the case of projections for the future also varies among the general circulation models used. In this regard local water abstraction projections might also be analysed in terms of the projected climate-driven water availability changes in the respective region.

There could be potential bias of the dataset due to one model providing data for the majority (LPJmL; 9 out of 16 including studies based on the MAgPIE model that uses some input from LPJmL) of the studies, however these studies also differ in terms of land type and area used for bioenergy cultivation, irrigation management, or structural parameters (carbon conversion efficiency/bioenergy demand trajectory) as can be seen in the spread in Figure 3.2, Figure A1.2, and the supplementary data (Stenzel et al., 2021c).

All of the studies targeted in this review also consider rainfed plantations that depend solely on green water stored in the soil (with added irrigation if necessary), however the amount of evapotranspired green water is only reported in a few of them. An overview of studies reporting global green water abstraction for bioenergy, which either do not consider irrigated BPs (Séférian et al., 2018; Smith and Torn, 2013; Smith et al., 2016), or do not specify where the source of the evapotranspired water is (King et al., 2013; Varis, 2007) is given in Figure A1.3. According to these studies, green water consumption of bioenergy ranges from 50 to over 3,000 km^3 GtC^{-1} of biomass harvest. Since this review focuses on blue water requirements, those estimates are not included in the main analysis.

Focusing on the blue water abstractions, allows us to directly compare them in the light of competition with other human water uses and those of aquatic ecosystems, potentially increasing overall water stress. A useful objective of future studies would be a more comprehensive quantification of the water requirements of bioenergy systems, partitioning sources into green and blue pathways and identifying potential means of increasing water use efficiency and decreasing blue water abstractions. However, the current review is timely since information on the relative magnitudes of green and blue water demands of large-scale bioenergy implementation, relative to other social and environmental needs, is needed now for the best decision-making and policy development.

3.4.2 Study differences in parameters choices and other assumptions

Study type. According to our literature review, estimating future global water abstractions of BPs is being approached with a variety of models and methodologies. Berndes (2002) uses projections based on measured evapotranspiration fluxes from field studies (e.g. Berndes and Borjesson 2001), combined with bioenergy demand scenarios (e.g. Nakićenović et al. 1998, p.72–75) to compute the global freshwater consumption of BPs. Hu et al. (2020) use a similar approach by inversely calculating biomass harvest demands for RCP2.6 (Van Vuuren et al., 2011) for three scenarios of carbon conversion factors, combined with literature values of water use efficiencies for two C4 grasses. Most studies rely on numerical simulation models, based on an energy (or NE) trajectory controlling the location, productivity and eventually water abstractions for BPs (here referred to as "demand driven studies"), or the aim to find the maximum energy (or NE) potential within given constraints of available land, water restrictions or management ("supply driven studies"). Examples for the former category of studies are De Fraiture et al. (2008); Mouratiadou et al. (2016); Humpenöder et al. (2018); Stenzel et al. (2019) and for the latter category Beringer et al. (2011); Jans et al. (2018); Fajardy et al. (2018).

Modeling framework. While Berndes (2002) and Hu et al. (2020) derived their results mainly from meta-analyses of existing literature and approximations of global water consumption by extrapolating current water use efficiencies for future energy demand scenarios, others are based on simulations from quite sophisticated global process models of different types. Bonsch et al. (2016), Mouratiadou et al. (2016), and Humpenöder et al. (2018) used the MAgPIE agroeconomic model determining the water withdrawal or consumption for BPs under different scenario constraints. Bonsch et al. (2016) specifically investigated the trade-offs between area and water withdrawals by comparing rainfed and irrigated BPs, while Humpenöder et al. (2018) analysed environmental and socio-economic indicators in bioenergy scenarios. The majority of studies considered here (Beringer et al., 2011; Heck et al., 2016b; Boysen et al., 2017b; Heck et al., 2018; Jans et al., 2018; Stenzel et al., 2019) were based on a single dynamic global vegetation model (DGVM), LPJmL, yet using different model setups and imposing varied constraints to water availability and use (biophysical potentials from LPJmL were also used as input to MAgPIE-based studies). Main study goals were global bioenergy potentials and the associated trade-offs with global water consumption, plantation area demand or planetary boundaries.

The water (and land) implications of increasing biofuel production in the future were analysed in De Fraiture et al. (2008) with the water use model WaterSIM and in Gerbens-Leenes et al. (2012) with the agricultural decision support tool CROPWAT. Yamagata et al. (2018) assessed the impact of large-scale BECCS deployment on land use, water resources, and ecosystem services using the global hydrological model H08 together with the terrestrial ecosystem model VISIT. Fajardy et al. (2018) base their analysis of the whole BECCS supply chain on the MONET value chain model, while Hejazi et al. (2014) employ a combination of GCAM (an IAM) in conjunction with the global hydrological model GWAM to quantify global water scarcity under several future climate change scenarios.

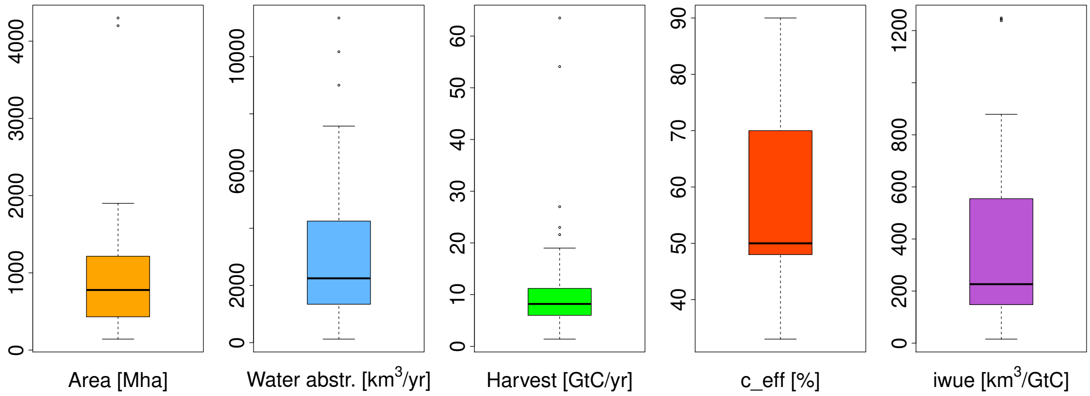


Figure 3.1: Range of key parameters (global estimates) determining projections of water abstractions for bioenergy in the scenarios examined (see supplementary data Stenzel et al. 2021c) presented as boxplots. Note that plantation area and carbon conversion efficiency (c_eff) are not reported in all studies. Inverse water use efficiency per biomass harvest (iwue) is calculated for each scenario, using the means of water abstractions and biomass harvest if ranges are given.

Bioenergy plantation area. The global potential plantation area identified as suitable for BPs differs hugely in size between 42 Mha in De Fraiture et al. (2008) (only biofuels) and 8,195 Mha in Hejazi et al. (2014), with the median area being 616 Mha (see Figure 3.1 and Figure A1.1). Reported maps show locations scattered around the globe (Stenzel et al., 2019), with clusters in Central Europe, North and South America and North-East China in Beringer et al. (2011) or South America and Central Africa in Bonsch et al. (2016). Note, however, that BP area size and especially location specific water use maps are not reported in every study, but would be crucial to compare and interpret the projected magnitudes of global freshwater consumption as determined by the water availability and requirements in the respective locations (King et al., 2013). Studies without explicit bioenergy locations thus need to be interpreted with caution.

The geospatial location of additional large-scale irrigation might also be relevant from the perspective of feedbacks with the climate system (Moore and Rojstaczer, 2002). Recently it was suggested that the influence of land cover change and especially irrigation on evapotranspiration are larger than expected (Van Noordwijk and Ellison, 2019; Ellison et al., 2019), such that moisture recycling through transpired irrigation water and moisture transport to downwind regions may be affected also by the biomass plantations. Thus, for example, as long as forests are not removed in order to grow the biomass material, the upwind production of additional biomass material could potentially have positive impacts on downwind rainfall and water availability (DeAngelis et al., 2010; Layton and Ellison, 2016). These atmospheric linkages make it all the more important to consider such interventions both strategically and spatially with the potential to find synergies in cases where upwind irrigation under high water availability might provide additional precipitation to dry downwind regions. New modelling approaches tracking atmospheric moisture pathways (Tuinenburg and Staal, 2020) or direct coupling of land-system and climate models (Pokhrel et al., 2017) help to better understand these processes.

The reported land types, which are projected to be converted to BPs, show a large variety covering marginal land (e.g. Smith et al. 2016), natural vegetation (e.g. Jans et al. 2018), partially excluding protected or vulnerable lands (e.g. Beringer et al. 2011). Some studies create new overall land-use patterns based on spatial and temporal optimization of costs (e.g. Humpenöder et al. 2018) or environmental impacts (e.g. Heck et al. 2018), others use existing exogenous projections for designated BP area (e.g. from RCP2.6-based studies in Boysen et al. 2017b). Conversion of cropland to bioenergy plantations is generally avoided (except in Yamagata et al. 2018 and Heck et al. 2016b). Current cropland extent amounts to 1,564 Mha (Klein Goldewijk et al., 2016). The potentially (theoretically) available land for biomass plantations today in each of the remaining categories would be: 385–472 Mha for marginal land (Campbell et al., 2008), 6,899 Mha for natural vegetation (Boysen et al., 2017b), 3,286 Mha for natural vegetation excluding protected or vulnerable land (Stenzel et al., 2019), and 441 Mha for the BP area in RCP2.6-SSP2 in 2100 (Boysen et al., 2017b).

Irrigation parameters. Within the studies that explicitly model irrigation of BPs, there is also strong variation in the parametrisation of the irrigation systems. Some studies allow potential irrigation, i.e. assuming unlimited availability of surface or groundwater and neglecting feedbacks resulting from water demands higher than available resources (Hejazi et al., 2014). Conversely, irrigation is in some studies simulated to be constrained by surface water availability (Beringer et al., 2011; Heck et al., 2016b), or even further constrained by additionally accounting for so-called "environmental flow requirements" (EFRs) to be withheld for protection of riverine ecosystems (Jans et al., 2018; Humpenöder et al., 2018; Stenzel et al., 2019). Additionally, the water losses due to different efficiencies of irrigation systems can in theory vary between $<$30 % for surface irrigation and $>$70 % for drip irrigation (productive share of the withdrawals in Jägermeyr et al. 2015). Irrigation efficiencies for BPs are typically assumed to be rather on the upper end of this range (e.g. 66 % in Humpenöder et al. 2018). Also the fraction of plantations that are allowed to be irrigated varies widely. In their "IrrExp" scenarios, Stenzel et al. (2019) e.g. allow for irrigation on all plantations which would benefit from this irrigation, only constrained by the availability of surface water and EFRs, while their "TechUp" and "Basic" scenarios are limited to 30 % of irrigated areas, those with high water productivities preferred.

Biomass feedstock. The majority of scenarios consider C4 grasses like *Miscanthus* or switchgrass (29/34), temperate (18/34), and tropical tree species (17/34) as bioenergy feedstock (e.g. Boysen et al. 2017b; Yamagata et al. 2018; Heck et al. 2018). Among the reviewed studies, only two consider first-generation bioenergy plants as feedstock like rapeseed, oil-palm, or sugar cane (De Fraiture et al., 2008; Gerbens-Leenes et al., 2012). Residues from agriculture or forestry, estimated to contribute up to 100 EJ yr^{-1} in 2050 (Bauen et al., 2009; Haberl et al., 2010), are discussed by Beringer et al. (2011)

but not included in their analysis. Stenzel et al. (2019) and Heck et al. (2018) include the one-time timber harvest from the land-use conversion of forests to biomass plantations. Fajardy et al. (2018) include wheat straw residues as biomass feedstock. However, in the context of the current review, major impacts on water can probably only be expected by designated large scale plantations.

Some studies assume yield productivity changes in the bioenergy harvest over the 21st century based on previous productivity increases observed in crop harvests (Bonsch et al., 2016; Mouratiadou et al., 2016; Humpenöder et al., 2018). There is also the argument that this increase of productivity might be more difficult to reach than for food crops, since the whole above-ground biomass is used for bioenergy production, instead of only a small ratio as in the case of food crops (Krausmann et al., 2013). Breeding programs might also yield significant potential for improved water use efficiencies in bioenergy crops.

Timing of bioenergy implementation. For demand driven studies crucial (but mostly exogenous) parameters are the starting year and trajectory for the BECCS demand, e.g. whether deployment is assumed to start in 2015 (Humpenöder et al., 2018) or in 2030 (Stenzel et al., 2019). Trajectories of the energy (or NE) demand (Boysen et al., 2017b; Hejazi et al., 2014; Berndes, 2002) which require higher yearly biomass yield demands at the end of the century will likely also lead to higher yearly irrigation requirements. The yearly water abstractions given in the studies are not always indicative of average irrigation water abstractions per year, since demand studies mostly report end of study period values (e.g. mean 2090-2099) where irrigated areas are at their maximum.

Carbon conversion efficiency. An important parameter in the BECCS process chain (and indirectly influencing the water demand of BPs) is the carbon conversion efficiency (c_{eff}), which we define as the overall fraction of harvested biomass carbon that can be sequestered and thus removed from carbon cycling. Gough and Vaughan (2015) report the capture rates of the CCS processes to be 85–90 %, but these ranges only describe the CCS efficiency, disregarding the supply chain carbon efficiency, which can be much lower. Smith and Torn (2013) give an overall conversion efficiency of 47 % for typical BECCS process chains. For our literature corpus, c_{eff} (if reported at all) ranges from 31–33 % (Bonsch et al., 2016; Fajardy et al., 2018; Yamagata et al., 2018) to 94 % (Hejazi et al., 2014) (Figure 3.1).

Other constraints. As already briefly discussed in the context of irrigation parameters, the studies from our literature corpus consider some other constraints to large-scale BECCS implementation, which are likely to also influence their freshwater abstractions. Limiting human intervention with the environment, specifically by respecting planetary boundaries (Rockström et al. 2009; Steffen et al. 2015) might limit the BECCS potential significantly as shown in Heck et al. (2018). Similarly, Bonsch et al. (2016) identify a trade-off between irrigation water and plantation area demand, which corresponds to trade-offs with planetary boundaries for freshwater use, biosphere integrity and land-system change. Additionally, economic constraints such as the accessibility of BPs, their distance to cities where most energy is needed, and the availability of large geologic storage capacity close to the locations of energy consumption are to be mentioned as further determinants of bioenergy water abstractions (e.g. considered in Fajardy et al. 2018).

3.4.3 Projections of global irrigation water abstractions for bioenergy plantations

From the 16 studies we synthesized 34 scenarios, for which we collected the projected freshwater abstractions and associated data (see supplementary data Stenzel et al. 2021c). We collected: type of study, modelling framework, bioenergy feedstock, land-type converted to biocrop plantation, whether global maps for bioenergy locations are included, whether withdrawal or consumption is reported, type of water (blue/green/grey), simulation year for which data is extracted, c_{eff}, plantation area, provided bioenergy and/or NEs (depending on study type).

The projections of potential future freshwater consumption for irrigation of BPs (125–11,350 $km^3\ yr^{-1}$) vary substantially due to differences in model structure, scenarios, study goals, and data input. Extreme cases are the FFICT-B2 scenario in Hejazi et al. (2014) and the Food First (FF) scenario in Jans et al. (2018), who simulate BP cultivation on 4,000–8,000 Mha with associated water withdrawals of 5,500–9,000 $km^3\ yr^{-1}$. These scenarios include extremely high amounts of irrigated BPs (Hejazi et al., 2014) or are maximum potential scenarios (largely unconstrained in terms of available area) (Jans et al., 2018), at least in the latter case not meant to be implemented as such. Assuming water use efficiencies of 585 $m^3\ t^{-1}$ for *Miscanthus*, Hu et al. (2020) project the water consumption on RCP2.6 consistent BP areas (431 Mha) to be up to 11,350 $km^3\ yr^{-1}$.

3.4.4 Bioenergy plantation water abstractions in light of water use in other sectors

The contemporary global green and blue water consumption on cropland is 5,000–10,000 $km^3\ yr^{-1}$ and 800–1,500 $km^3\ yr^{-1}$, respectively (Hoff et al., 2010; Jägermeyr et al., 2015; Rosa et al., 2018). Runoff feeding these appropriations globally sums up to approximately 40,000 $km^3\ yr^{-1}$ (Sperna Weiland et al., 2010; Gerten et al., 2013a), of which however only 30–40 % is geographically and temporally accessible to humans (Postel et al., 1996).

To contextualize the above-discussed estimations of irrigation water abstractions for bioenergy, earlier projections of future water use for the three main other sectors agriculture, industry and households are collected (Alcamo et al., 2007; Shen et al., 2008; Hanasaki et al., 2013a,b; Wada and Bierkens, 2014; Wada et al., 2016; Graham et al., 2018) and compiled for comparison (see Figure 3.2 and supplementary table file). Agriculture is globally the largest water using sector among the three, with a global total irrigated area reported to be 306 Mha in 2000 (Siebert et al., 2015). Estimates of present (between 2000 and 2010) agricultural water withdrawal are in the range 2,402–3,214 $km^3\ yr^{-1}$.

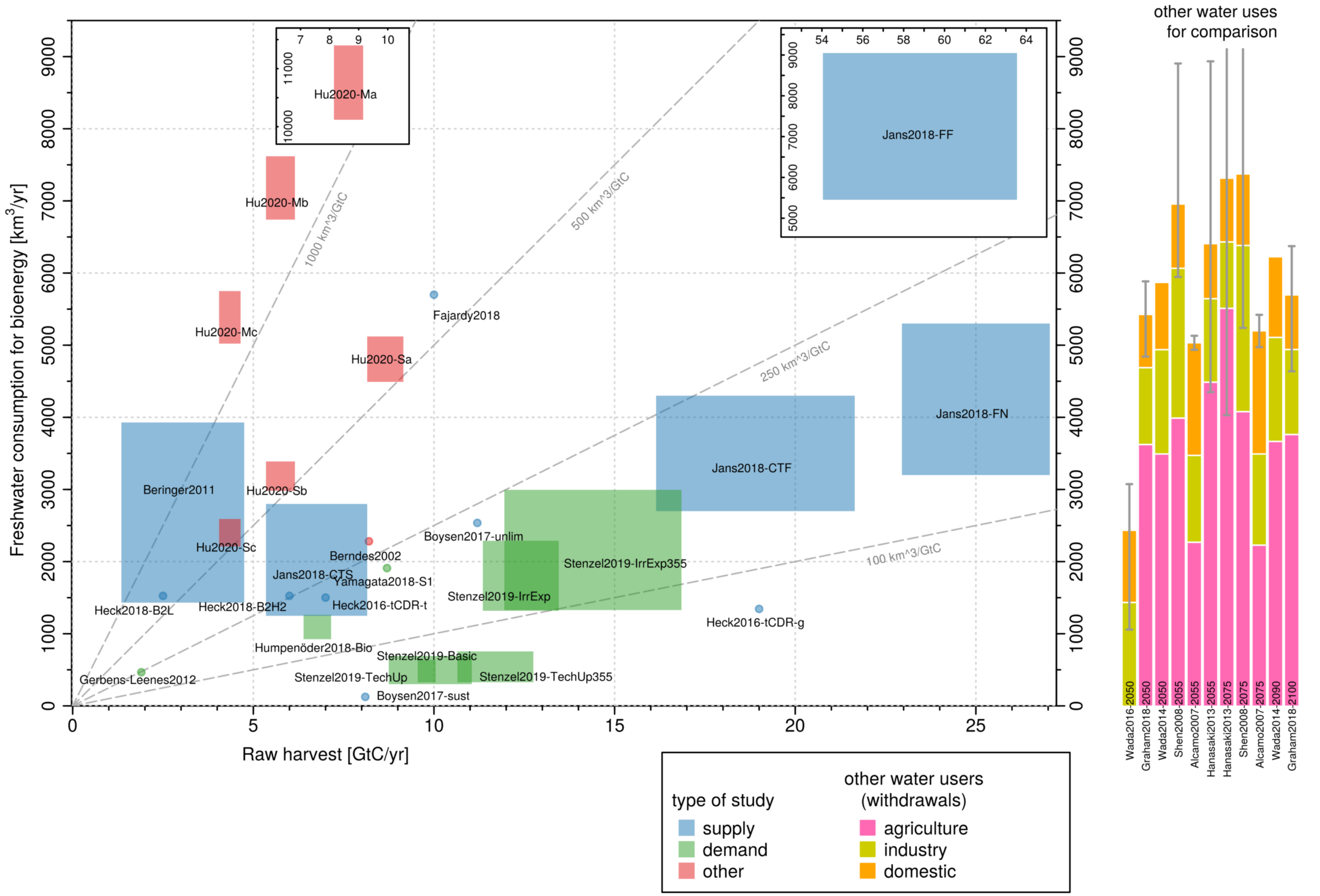


Figure 3.2: Overview of scenarios of reported values of global blue water consumption required for bioenergy production through biomass plantations (inlays show scenarios outside the plotting region). Scenarios are characterized by freshwater consumption for bioenergy plotted against raw harvest (inferred from reported biomass based energy or negative emissions). They can provide ranges in water withdrawals or raw harvest (illustrated by boxes), or contain single values (depicted by circles). The type of study is marked by the colour. Results for studies which report blue water withdrawals can be found in Figure A1.2, studies of green water consumption in Figure A1.3. For contextualization, projections for other water uses (withdrawals) are shown to the right, together with their uncertainty ranges. Names of the bioenergy scenarios are constructed as {author}{publication year}-{scenario name}, those of "other water use" scenarios as {author}{publication year}-{simulation year}.

Future agricultural water withdrawal is projected by grid-based numerical hydrological or crop growth models. For the mid (around 2050) and the late 21st century (between 2075 and 2090), estimates range between 2,256–6,037 $km^3\,yr^{-1}$ and 2,211–8,434 $km^3\,yr^{-1}$, respectively. These wide ranges in estimations are primarily attributed to the assumption on future irrigated area, which differ widely, as in the case of BP projections. The lower ends assume that irrigated area hardly increases in the future, based on the view that land for new irrigation projects is no longer available (e.g. Alcamo et al. 2007 and the low-end scenario of Hanasaki et al. 2013b). The high-end projection assumes that irrigated area increases at a rate of 0.6 $\%\,yr^{-1}$ (i.e. the high-end scenario of Hanasaki et al. 2013b). Another case assumes that agricultural water use grows in proportion to the total population as observed in the latter half of the 20th century (Shen et al., 2008). Other assumptions with respect to changes in irrigation efficiency, crop intensity and climate change further widen the range of estimates.

Industry and domestic water use are the second and third largest water using sectors. The estimates of present industrial and domestic water withdrawals are in a range of 691–894 $km^3\,yr^{-1}$ and 328–474 $km^3\,yr^{-1}$, respectively. Future industrial and domestic water withdrawal is projected using empirical approaches. For instance, Alcamo et al. (2003) and Alcamo et al. (2007) develop nationwide regression models to model water withdrawal in response to key drivers (e.g. population, income, electricity production, efficiency improvements) used in an exponential form to express the empirical facts that per activity water use continuously drops through time. Future industrial water withdrawals in the middle and the late 21st century are estimated to range between 433–3,313 $km^3\,yr^{-1}$ and between 246–3,772 $km^3\,yr^{-1}$, respectively. These ranges primarily reflect differences in efficiency improvement settings. As for domestic water, ranges are 628–1,563 $km^3\,yr^{-1}$ and 573–1,726 $km^3\,yr^{-1}$, respectively, for the two future time periods.

The median (first and third quartile) of total water withdrawal for the present, the mid- and the late 21st century is 3,770 (3,724–3,824), 5,806 (5,311–6,378), and 6,076 (5,063–6,984) $km^3\,yr^{-1}$, respectively.

Figure 3.2 and Figure A1.2 indicate that 19 out of 34 estimations for global additional irrigation water withdrawal for bioenergy exceed 2,000 $km^3\,yr^{-1}$, which corresponds to half of present water withdrawals. This additional volume is roughly equivalent to the differences in total water withdrawal between SSP1 (4,295 $km^3\,yr^{-1}$), SSP2 (6,369 $km^3\,yr^{-1}$), and SSP3 (8,827 $km^3\,yr^{-1}$) in 2050 (Hanasaki et al., 2013b) – (SSP: shared socioeconomic pathway). A significant increase in water withdrawal for biomass production is likely to intensify water stress in respective regions, if not carefully planned in view of other water uses. The estimated global total water stressed population for SSP1, SSP2, and SSP3 are 2,853; 3,642 and 4,265 million people. Although the water usage is different, it implies that 2,000 $km^3\,yr^{-1}$ of additional irrigation may increase the water-stressed population by 600–800 million people (Hanasaki et al., 2013b). Importantly, integrative studies that account for all major water users including bioenergy in a consistent framework, at global scale yet spatially explicit, are basically lacking.

The future price of biomass, as well as the value of freshwater likely depends on political decisions (Klein et al., 2014) or market forces also in other sectors (Dinar and Mody, 2004). Integrated assessments of the combined effects in a globally monetized biomass and food market with potential limitations of irrigation water withdrawals (Hogeboom et al., 2020) or associated high costs (De Fraiture and Perry, 2002), especially under conditions of continued climatic change, poses interesting avenues for further research.

3.4.5 Inverse water use efficiency relating freshwater abstractions and harvest

Reported primary bioenergy (energy content of the biomass harvest to be converted to electricity) ranges from 40 to 2,350 EJ yr^{-1}, while NEs range from 1.2 to 10.0 GtC yr^{-1}. After converting primary bioenergy and NEs to initial biomass harvests (see section 3.3.2), we find the projections of global freshwater abstractions per harvested biomass (iwue) to be in the range of 15–2,761 km^3 GtC^{-1} (15–1,250 km^3 GtC^{-1}, if the mean scenario values are used – Figure 3.1). This large range shows that freshwater withdrawals or consumptions do not linearly depend on the amount of cultivated biomass – it is rather the large variety in other parameters (which cannot be made comparable) that primarily discriminates the scenarios (Figure 3.2 and Figure A1.2). Scenarios "sust" from Boysen et al. (2017b), "Basic", "TechUp", and "TechUp355" from Stenzel et al. (2019) and "tCDR-g" from Heck et al. (2016b) demonstrate iwue values below 100 km^3 GtC^{-1} (15, 50, 49, 46 and 71 km^3 GtC^{-1}).

In the theoretical scenario tCDR-g in Heck et al. (2016b), no additional BP locations are determined but all existing cropland in year 2005 is assumed to be replaced with BPs and assumed to be irrigated very efficiently, which results in high harvests and thus low iwue. In the "sust-scenario" considered in Boysen et al. (2017b), only 40 out of a total 441 Mha BP area are considered to be irrigated, but the authors do not provide values to discriminate the respective harvests. In their "TechUp-WM" scenario, Stenzel et al. (2019) assume a high c_{eff} of 70 % together with EFR restrictions on freshwater withdrawals, which keeps iwue below 100 km^3 GtC^{-1}. The highest projected iwue values are from the M*-scenarios from Hu et al. (2020) (1,102–1,402 km^3 GtC^{-1}), Beringer et al. (2011) (315–2,761 km^3 GtC^{-1}), the "Baseline" (909 km^3 GtC^{-1}) and "FFICT-B2" (849 km^3 GtC^{-1}) scenario from Hejazi et al. (2014) and the "Low-Yields" scenario from Bonsch et al. (2016) (723 km^3 GtC^{-1}). Here we denote, that the very high value (2,761 km^3 GtC^{-1}) for Beringer et al. (2011) might be an artefact of how we handle data value ranges, since the scenario producing the lowest energy yields, is most likely not the one with the highest water consumption, so that the scenario is probably rather following a trend of 1,000 km^3 GtC^{-1}.

However we are still surprised to find that supply driven studies do not consistently suggest higher harvest than demand driven studies. This could mean that even demand driven studies are operating at the limits of the Earth system, and supply driven studies, especially when considering sustainability constraints, cannot provide more negative emissions than are already demanded for ambitious climate targets like 1.5 °C.

Only a few global studies consider biofuels (e.g. Gerbens-Leenes et al. 2012; De Fraiture et al. 2008) which (aside from the irrigation water abstractions for the bioenergy feedstock considered in this review) require additional water for processing. It should be noted that the additional water abstractions for the biofuel refinement process (on top of the in-field water abstractions) are considered in many regional life cycle assessment studies and assumed to be about 4 units of water per unit of ethanol according to Fike et al. (2007) and Keeney and Muller (2006). General assessments including both primary bioenergy and biofuels would need to consider different conversion efficiencies for the different biomass pathways (as in Bonsch et al. 2016, or Heck et al. 2018).

3.5 Conclusions

We discover a large range of parameters and scenario criteria (Table 3.1 and more detailed in the supplementary dataset Stenzel et al. 2021c) that are crucial for estimating the irrigation water abstractions for BPs. We are not able to quantify the contribution of each parameter, however strong dependencies are expected for the targeted primary bioenergy or negative emissions amounts, the assumed carbon conversion efficiency, and the assumed plantation area.

However a number of necessary parameters were not documented in the publications needed for a full assessment of the hydrological implications of widespread BP deployment. Thus we recommend that all scenario parameters be reported in future publications on water use (including irrigation) of BPs, enabling more straightforward interpretation and comparison of results. A minimum set of reported parameters, ideally spatially detailed, should in our view include the complete water balances of BPs (including partitioning of blue and green water), water use efficiencies of the respective plant types, rainfed and irrigated BP locations (including total area and climatic conditions), and total biomass harvest amounts.

We find the global water withdrawals for irrigation of biomass plantations estimated from the available literature to be in the range of 128.4–9,000 $km^3\ yr^{-1}$ (consumption: 125–11,350 $km^3\ yr^{-1}$), compared to about 1,100–11,600 $km^3\ yr^{-1}$ for the sum of other (agricultural, industrial, and domestic) water withdrawals and thus at similar magnitude. It needs to be noted that the water abstractions for bioenergy production would come on top of (or compete with) that for the other uses.

Surprisingly, there is no clear relationship (e.g. linear) between water abstractions and total bioenergy production. However, by comparing the freshwater abstractions per harvested biomass, we find that most of the scenarios fall between 100–1,000 $km^3\ GtC^{-1}$. The full range of 15–1,250 $km^3\ GtC^{-1}$

for biomass harvest implies that, given a carbon conversion efficiency of 50 %, we might need 99–8,250 km^3 to reach NEs of 3.3 GtC yr^{-1} as projected to be necessary by Smith et al. 2016.

The studies analysed in this manuscript span a publication time of almost 20 years, such that there might be significant changes even among different versions of the same model (e.g. GCAM in Hejazi et al. 2014 vs. in Graham et al. 2018, as discussed in Calvin et al. 2019), suggesting the need for a concerted model intercomparison for projections of bioenergy water demands under controlled assumptions and with the latest model versions.

These additional water abstractions for bioenergy, which are at the same magnitude of water demand projections for conventional usage seem to paint a picture of a future where water scarcity can become a global and perpetual issue.

It would have been desirable to also include regional studies into our analysis, but this would have required more information than is usually provided, to for example analyse local yield and/or water productivity, and data on other water use sectors.

Besides the freshwater abstractions, potential impacts of BPs mostly stem from the implied land-cover and land-use conversion. Replacing natural vegetation with bioenergy crops could affect biodiversity, while, if grown on cropland, they could affect food security. Overall, most of the analysed scenarios do not explicitly replace existing cropland by BPs. This in turn means that most studies (at least implicitly) assume investments in additional infrastructure for irrigation assuming it is economically justifiable. Some scenarios also explicitly protect vulnerable natural areas. These considerations promote the use of marginal or degraded lands for BPs.

This review provides a first comprehensive overview of the current literature on global projections of the freshwater abstractions for irrigated bioenergy plantations. Furthermore, it is the first study that highlights the potential dependence on irrigation for BECCS to deliver NEs for ambitious climate targets and calls for further investigation and reporting on the underlying (model) assumptions. Integrated assessments that consider all water use sectors (including bioenergy, along with potential trade-offs based on detailed understanding of local limitations) are highly desirable and are crucial to get a better understanding of the limits and options of future water consumption.

3.6 Acknowledgements

This study was funded by the CE-Land+ project of the German Research Foundation's priority program DFG SPP 1689 on "Climate Engineering – Risks, Challenges and Opportunities?". Part of the research was developed during the Young Scientists Summer Program at the International Institute for Applied Systems Analysis, Laxenburg (Austria) with financial support from the German National Member Organization.

4

Freshwater requirements of large-scale bioenergy plantations for limiting global warming to 1.5 °C

An edited version of this chapter has been published in the journal Environmental Research Letters:

Stenzel, F., D. Gerten, C. Werner, and J. Jägermeyr. Freshwater requirements of large-scale bioenergy plantations for limiting global warming to 1.5 °C. *Environmental Research Letters*, 14(8):084001, 2019. `https://doi.org/10.1088/1748-9326/ab2b4b`

4.1 Abstract

Limiting mean global warming to well below 2 °C will probably require substantial negative emissions (NEs) within the 21st century. To achieve these, bioenergy plantations with subsequent carbon capture and storage (BECCS) may have to be implemented at a large scale. Irrigation of these plantations might be necessary to increase the yield, which is likely to put further pressure on already stressed freshwater systems. Conversely, the potential of bioenergy plantations (BPs) dedicated to achieving NE through CO_2 assimilation may be limited in regions with low freshwater availability. This paper provides a first-order quantification of the biophysical potentials of BECCS as a negative emission technology contribution to reaching the 1.5 °C warming target, as constrained by associated water availabilities and requirements. Using a global biosphere model, we analyze the availability of freshwater for irrigation of BPs designed to meet the projected NE to fulfil the 1.5 °C target, spatially explicitly on areas not reserved for ecosystem conservation or agriculture. We take account of the simultaneous water demands for agriculture, industries, and households and also account for environmental flow requirements (EFRs) needed to safeguard aquatic ecosystems. Furthermore, we assess to what extent different forms of improved water management on the suggested BPs and on cropland may help to reduce the freshwater abstractions. Results indicate that global water withdrawals for irrigation of BPs range between $\sim$400 and $\sim$3,000 $km^3\,yr^{-1}$, depending on the scenario and the conversion efficiency of the carbon capture and storage process. Consideration of EFRs reduces the NE potential significantly, but can partly be compensated for by improved on-field water management.

4.2 Introduction

With the Paris Agreement (UNFCCC, 2015), the international community has agreed to aim for a global mean temperature (GMT) increase of *well below 2 degrees* compared to pre-industrial levels, and *pursue efforts to limit it to 1.5 degrees*. Since the remaining carbon emissions budget for such ambitious climate goals is very small (Fuss et al., 2014), the use of negative emission technologies (NETs) seems almost inevitable (Minx et al., 2018; Rogelj et al., 2018; Rockström et al., 2017). The necessity for NET deployment might even increase, should efforts of decarbonization be less pronounced or come into action later than envisioned today.

The NET most widely used in projections for the 21st century is bioenergy plantations (BPs) with subsequent carbon capture and storage (BECCS) (Schleussner et al., 2016; Fuss et al., 2014). BECCS utilizes fast growing plant species to convert atmospheric CO_2 to biomass, which is regularly harvested and burned for energy generation or fermented to produce biofuels. The CO_2 from the exhaust or by-product of fermentation is captured, compressed, stored permanently (e.g. in geologic reservoirs), and thus removed from the natural carbon cycle (Lenton, 2010; Caldeira et al., 2013). BECCS could potentially provide large amounts of negative emissions (NEs), but in turn competes with agriculture and other uses such as ecosystem conservation for land requirements. Different (portfolios of) NETs (Werner et al., 2018; Minasny et al., 2017) or alternative mitigation pathways (Van Vuuren et al., 2018) are receiving more and more attention, but bioenergy utilization will likely be significant during the 21st century (IPCC, 2018), since it is relatively cheap, compared to Direct-Air-Capture and more land-effective than afforestation (Smith et al., 2016). Therefore our study provides additional value in support of making deployment decisions based not only on economic, but also eco-hydrological reasoning.

The cultivation of plants to generate biomass at the level needed to satisfy high NE demands requires extensive plantation areas (Boysen et al., 2017b), and even more so, if realized under rainfed conditions (Beringer et al., 2011). Because of the land scarcity, future BPs are likely to be irrigated to a significant amount in order to expand into more marginal terrain. In view of already existing water stress in many regions (Wada et al., 2011; Schewe et al., 2014), the quantification of freshwater demands for large-scale BECCS is critical but remains largely unknown – especially under the assumption not to constrain existing demands from agriculture, industry, and domestic users. Furthermore, there is a need to more systematically explore the NE constraints imposed by freshwater limitations (including the trade-off with flow requirements to sustain freshwater ecosystems), and to what extent such limitations could be alleviated by optimal water management on agricultural and BP areas.

Previous studies have provided first assessments of freshwater demands corresponding to large-scale BECCS deployment required to constrain GMT rise. Berndes (2002) projected 2,281 $km^3\ yr^{-1}$ of additional withdrawals for biomass-based energy production of 304 EJ yr^{-1} in 2100 (mainly from first generation BPs), while more recent estimates from Smith et al. (2016) suggest 720 $km^3\ yr^{-1}$ of additional water use to achieve NEs of 3.3 Gt C yr^{-1} in 2100. A further model study by Bonsch et al. (2016) arrived at an additional water demand of 3,362–5,860 $km^3\ yr^{-1}$ for generating 300 EJ yr^{-1} in 2100. The large range of these estimates results from different assumptions on productivity increases, the associated BP area demand, and irrigation water productivity levels. Accounting for diverse spatially explicit nature protection areas, Beringer et al. (2011) estimate a bioenergy water demand in the range of 1,481–3,880 $km^3\ yr^{-1}$ to generate 130–270 EJ. More recently Yamagata et al. (2018) suggested 1,910 $km^3\ yr^{-1}$ of consumptive water demand for bioenergy crops to achieve NEs of 3.3 Gt C yr^{-1}, while Séférian et al. (2018) estimate the water demand for producing 220–270 EJ in 2100 to be only 178 $km^3\ yr^{-1}$, which is probably a result of strong restriction of irrigation and model limitations. Jans et al. (2018) project a demand of 1,500–5,000 $km^3\ yr^{-1}$ to generate 200–1,000 EJ, while also securing environmental flow requirements (EFRs) with the prospect of maintaining freshwater ecosystems in a good state.

The large span in projected water demands as a result of the diverse methodologies applied motivates a more systematic and internally consistent approach. The present study comprehensively quantifies how much freshwater for irrigation of BPs will potentially be needed to constrain GMT rise to 1.5 °C above pre-industrial levels by the end of the century. It advances previous studies through process-based and spatio-temporally explicit simulations of water use and water consumption of BPs (in addition to other sectors), considering a range of irrigation intensities (including a rainfed option), water management improvements, EFR protection goals, a range of carbon conversion efficiencies (percentage of carbon from harvest of BPs that is permanently removed from the carbon cycle), and their combinations (Table 4.1). The water requirements under each of these setups are evaluated for yearly carbon sequestration demands simulated to follow a prescribed trajectory based on NE trajectories for a 1.5 °C climate from Rogelj et al. (2015) (Figure B2.1), representative of the upper end of the set of exclusive 1.5 °C scenarios (those that are not within the ranges of *likely* or *medium* 1.5 °C scenarios). The respective NE demands ramp up from 0.54 Gt C in 2030 to 5.45 Gt C in 2100. The scenarios analysed in Rogelj et al. (2015) already take into account a wide range of technologies to reduce emissions, including an increasing global carbon price which is assumed to lead to a lowering of total energy demand, increasing energy efficiency, carbon capture and storage in remaining fossil fuel energy generation plants, greater use of bioenergy in primary energy generation, electrification of the transport sector, and fossil fuel replacement (especially in the transport sector) by biofuels (Bauer et al., 2018). By applying the NE demand curve, we implicitly incorporate these underlying model assumptions of the socio-economic scenarios consistent with 1.5 °C. The focus of our analysis is on the sequestration of carbon via BECCS that could serve to achieve the prescribed NE targets, above and beyond the effects of these other transformations, and specifically on the associated water requirements. We do not however consider the economic aspects of implementation of such strategies, which are beyond the scope of the current analysis.

The total sequestration demand corresponding to this target is 255 Gt C over 2030–2100. To account for the possibility of partial or failed mitigation (cf. Werner et al. 2018), and, thus, a higher NE demand for compensating remaining emissions, a more ambitious total sequestration demand of 355 Gt C is also explored, obtained by linearly up-scaling the original yearly demand.

To account for limited land availability, only areas outside of current urban and agricultural land as well as areas of conservation interest are considered for conversion. All simulations are performed with the Dynamic Global Vegetation Model LPJmL, which computes terrestrial water cycling coupled to the carbon balance and vegetation growth of BPs alongside agricultural and natural vegetation, at daily time steps on a global 0.5 degree grid (Schaphoff et al., 2018b). LPJmL dynamically represents land surface processes such as discharge routing, crop growth, and water use efficiency, as well as yield responses to various stresses in any given grid cell. These features allow to dynamically choose the most productive BP type, based on local soil type, climate, and management options available.

Analysis is driven by the research question whether and under which constellations (degree of irrigation, consideration or neglect of EFRs, on-field water management) the targeted NE demands can be met while minimizing the additional pressure on global freshwater resources.

4.3 Methods

4.3.1 Scenarios

We compare the water requirements associated with the two sequestration demands (cumulative 255 Gt C and 355 Gt C between 2030 and 2100, with annual contributions as in Figure B2.1) for four different water use scenarios: rainfed only (RF), unconstrained irrigation withdrawals (IRR), availability-constrained irrigation respecting environmental flow requirements (EFR), and the latter combined with improved crop water management WM). For each of them, sub-scenarios are evaluated, considering a Basic parameter setting representing low-technology BECCS with only a fraction of the yield being irrigated, and two technologically more ambitious pathways (increased conversion efficiency - TechUp and irrigation expansion IrrExp) (see Table 4.1). BPs were only considered to be grown on areas outside of urban and agricultural land as well as areas of conservation interest. The remaining areas were consecutively (starting with the highest ratio of net biomass yield per irrigation water per area) converted to BP plantations until the respective sequestration goal was reached (see below). The scenarios were all computed independently of each other.

In scenario RF, only rainfed BPs were allowed to be cultivated; the extent of food cropland (see Potential area extent of BPs) and assumptions on irrigation system and extent of irrigated area (Jägermeyr et al., 2015) were fixed at the state of 2015 in this and all other scenarios, as it is beyond the scope of this study to account for simultaneous changes in food demand and agricultural area. RF also serves as a reference scenario for global water withdrawals for purposes other than BPs (households, industries, livestock (HIL), and irrigated agriculture). As irrigation of BPs is absent, this scenario has the least additional impact on freshwater resources (aside from indirect impacts on stream-flow due to a change in evapotranspiration (ET) of BPs, compared to the previous land use).

In IRR, sprinkler-irrigated herbaceous BPs and drip-irrigated woody BPs (for more information on BP types see LPJML model) can be grown in any suitable grid cell as long as there is enough freshwater available in rivers, lakes, and reservoirs (Jägermeyr et al., 2017). However, if irrigation would not increase yields by more than 50 % (determined in an extra simulation, see below), rainfed BPs are assumed instead in order to irrigate only those BPs, where irrigation increases the yield significantly. Irrigation, as for crops, is applied on a daily basis, when soil moisture falls below a plant-type specific threshold. HIL demand is assumed to be prioritized over irrigation water demand in all scenarios, using data from Flörke et al. (2013). In case there is not enough water left for meeting the demand of agricultural crops and BPs, the allocation of the available water is distributed according to the ratio of the respective areas. In this scenario there are no constraints to water withdrawals, thus representing a case with the largest potential withdrawals and the highest NE potential.

In the EFR scenario, the daily amount of available water for irrigation in a grid cell is capped. The EFRs are calculated according to the Variable Monthly Flow (VMF) estimation method (Pastor et al., 2014), which classifies months as low-, medium-, and high-flow months and allocates 60 %, 45 %, and 30 % of the flow for ecosystem purposes, respectively. EFRs are determined as 30-yr averages from a simulation based on historical land use (Jägermeyr et al., 2017) and the climate of the period 1970–1999. Hence, only water in excess of these reference EFRs is allowed to be used for BP irrigation in the future period. If EFRs are transgressed in a river basin (determined from the outflow cell) solely due to non-BP withdrawals, only rainfed BPs are assumed to be cultivated there.

Finally, scenario WM assumes that in addition to the EFR setup, advanced water management strategies are applied on both food cropland and BPs. They correspond to practices such as mulching, local run-off collection for supplemental irrigation during dry spells, modified irrigation thresholds, and soil management practices (see also LPJmL model and description in Jägermeyr et al. 2016).

For each of the water management scenarios we consider BP variants with different assumptions on the carbon sequestration demand (seq), carbon conversion efficiency (c_{eff}), and the maximum BP irrigation fraction (irr_{frac}). c_{eff} defines, how much of the carbon from the harvested biomass can be permanently removed from the carbon cycle (50 % or 70 %). The remaining carbon would eventually be transported back to the atmosphere and thus not permanently removed. A BECCS life-cycle assessment by Smith and Torn (2013) reveals overall conversion efficiencies of 47 %, while capture rates of CCS processes typically achieve 85–90 % (Gough and Vaughan, 2015). Technological change is likely to improve the efficiencies by reducing losses over time, which motivates our ambitious level of carbon conversion efficiency for the whole BECCS process-chain of 70 %. The maximum BP irrigation fraction (irr_{frac}) indicates the maximum level of BP irrigation (1.0 – all BPs can potentially be irrigated; 0.33 – at most a third of the BPs can be irrigated, roughly representing circumstances where economic or other constraints to irrigation infrastructure apply; 0 for scenario RF).

In the Basic parameter set we consider the NE demands of the regular emission pathway with no mitigation failure (seq=255 Gt C), a moderate carbon conversion efficiency (c_{eff}=50 %) and a moderate irrigation fraction (irr_{frac}=33 %). In the parameter sets TechUp and IrrExp, the parameters are changed to c_{eff}=70 % and irr_{frac}=1.0, respectively. In order to account for increased NE demands caused by failed mitigation actions, we apply the sets TechUp355 and IrrExp355 which use the same parameters for c_{eff} and irr_{frac} as TechUp and IrrExp, but the sequestration demand is set to 355 Gt C (see Table 4.1).

4.3.2 Potential area extent of BPs

The maximum land area that can be converted to BPs (fraction of 0.5 degree grid cell) was derived by excluding current cropland (Frieler et al. 2017, in year 2015 based on HYDE 3.2 by Klein Goldewijk et al. 2016), secondary forest areas for industrial round-wood production and urban build-up areas (Hurtt et al., 2016), intact forest landscapes (Potapov et al., 2017), wetlands (Lehner and Döll, 2004), and areas of conservation interest. Areas of biodiversity concern are derived from a binary dataset

Table 4.1: Parameterization of BP simulations and respective water management assumptions (RF, IRR, EFR, WM). Each water management scenario is simulated for five different BP parametrisations (Basic, TechUp, IrrExp, TechUp_{355}, IrrExp_{355}). The latter two refer to a higher sequestration target of 355 Gt C. irr_{frac} – maximum globally irrigated BP yield share (1.0 – all BPs can potentially be irrigated; 0.33 – at most a third of the BPs can be irrigated); c_{eff} – fraction of the carbon from the harvested biomass, which can be permanently removed from the carbon cycle (50 % or 70 %)

Scenario	**RF** Rainfed	**IRR** Unconstrained withdrawals	**EFR** Respect Environmental Flow Requirements	**WM** Water management
Irrigation of BPs	no	yes	yes	yes
Environmental flow protection	no	no	yes	yes
Water Management	no	no	no	yes

Parameter set	**Basic**	**TechUp**	**IrrExp**	**TechUp_{355}**	**IrrExp_{355}**
Maximum BP irrigation fraction (irr_{frac})	0.33	0.33	**1.0**	0.33	1.0
Carbon conversion efficiency (c_{eff})	50%	**70%**	50%	70%	50%
Carbon sequestration goal (seq)	255 Gt C	255 Gt C	255 Gt C	**355 Gt C**	**355 Gt C**

developed in this study, considering regions crucial to ecosystem functioning (see Figure 1a, a similar map is also used in Werner et al. 2018). Previous approaches usually preserved fractions of grid cells for conservation (Beringer et al., 2011; Boysen et al., 2016) rather than excluding entire cells, which can be interpreted as a land sparing approach. Here, a grid cell is excluded from conversion to BPs for reasons of biodiversity protection if it is covered by the World Database on Protected Areas (UNEP-WCMC, 2018) or if located within Biodiversity Hotspots (Mittermeier et al., 2011). In addition, we incorporated a catalogue on endemism richness, assuming plants as proxies for all floral and faunal species (Kier et al., 2009), conserving all areas with an endemism richness above the global average (> 21.66 endemic species/km^2). Finally, a dataset on threatened species (mean value of amphibians, birds, and mammals) was included (Pimm et al., 2014), based on which we assume cells to be protected where more than 3 % of all species are currently threatened.

The global area potentially suitable for BPs according to our configuration sums up to 3,286 Mha (Figure 4.1b). This would be more than twice the current cropland area. Large portions of this area, however, can not sustain BPs with yields above the minimum yield threshold of 2.5 t C ha^{-1} yr^{-1} due to climatic conditions, or are associated with too high land-use change (LUC) emissions due to the conversion of natural land to a BP (Harper et al., 2018; Houghton et al., 2012). We only consider grid cells if the mean yield for the period from plantation start until 2099 is above the harvest threshold. To calculate the LUC emissions as part of the carbon budget, we compare the size of litter, soil and vegetation carbon pools before and after the conversion to BPs and only consider sites where LUC emissions are at least two times compensated for by the net sequestration amount, excluding areas where plantation of bioenergy would only be marginally useful. To choose the most suitable type of BP for each grid cell (see below for bioenergy functional types in LPJmL), five model runs (assuming plantation on all potential areas with the same type of BP – woody, irrigated woody, herbaceous, irrigated herbaceous, no BP) were performed for scenarios IRR, EFR, and WM. These were used to determine the potential yields and water demands for all grid cell shares available for conversion to BPs in each simulation year. For RF three such pre-runs (woody, herbaceous, no BP) were sufficient, since irrigation is disallowed.

The net yield (**nY**) for all four possible BP types (rainfed vs. irrigated and woody vs. herbaceous) is given by the conversion efficiency (**c**$_{eff}$), the yield of the respective bioenergy plant (**beY**), and the potential timber yield from the initial land-use conversion (**tY**) :

$$nY = c_{eff} \cdot 0.475 \cdot (beY + tY) \tag{4.1}$$

where c_{eff} defines the percentage of the harvested carbon sequestered and thus extracted from the atmosphere; the factor 0.475 describes the average carbon content of dry biomass from Schlesinger and Bernhardt (1991, p.120).

In every grid cell, the net yield is compared with the associated LUC emissions (see Figure B2.2). For most regions, BPs reduce the natural carbon holding capacity and thus have positive LUC emissions. In regions such as eastern Australia, the central/northern United States, or southern Africa, however, managed BPs can have enhancing carbon sequestration effects, besides the yield. BP implementation is only simulated if the plantation productivity compensates for the LUC emissions at least two times with the total net sequestration. As a further constraint, BPs are only irrigated if the productivity increases by at least 50 % over rainfed systems. For the runs with EFR constraints, the most productive rainfed BP type is chosen if the whole basin or the current cell is already transgressing the EFR requirements. Subsequently, all cells are ranked according to their yield/irrigation water ratio (irrigation water amount is set to 1 if it is a rainfed cell) and from this record, the cells are chosen consecutively (meaning the cell with the highest ratio – least water per yield – is selected first) until the sequestration goal of the respective year is reached. Thereby, overall productivity in each grid cell determines both the type of BP and irrigation, which in turn depend on the soil type, climate conditions, and water availability. This results in unique spatial patterns for each scenario (see Figure B2.2).

4.3.3 LPJmL model

All simulations were conducted with the process-based Dynamic Global Vegetation Model LPJmL (Schaphoff et al., 2013, 2018b), which has recently been evaluated against various data sets from in-situ measurement sites, satellite observations, and agricultural yield statistics in Schaphoff et al. (2018a). The model considers 67420 land grid cells on a 0.5° x 0.5° global grid. It simulates terrestrial carbon fluxes for establishment, growth, and productivity of natural vegetation (computed dynamically based on climatic conditions), agricultural crops, and pasture (Bondeau et al., 2007), as well as water fluxes like ET, irrigation, and river routing (Gerten et al., 2004; Rost et al., 2008; Biemans et al., 2011). For 12 crop functional types calibrated to match national yield statistics (Fader et al., 2010) and a group of other annual and perennial crops, sowing dates are dynamically calculated (Waha et al., 2012), but here fixed after year 1999.

The model also considers two types of second-generation bioenergy crops. Woody bioenergy crops are parametrised as willows or poplars for temperate regions and *Eucalyptus* for the tropics. Herbaceous bioenergy crops are parametrised as *Miscanthus* or switchgrass. Herbaceous BPs are assumed to be harvested once the above-ground carbon storage reaches 400 g m^{-2}, but at least once a year. Bioenergy trees are harvested every eight years, with a maximum plantation life time of 40 years before total clearance and regrowth of saplings. The computed yields have been evaluated against field data by Beringer et al. (2011) and Heck et al. (2016b).

Dependent on the scenario, managed areas can be rainfed or irrigated, which determines the source of water to fulfil the demand of the plants to be either only precipitation water or precipitation and additional water from local storage or main discharge of the respective grid cell and neighbouring cells.

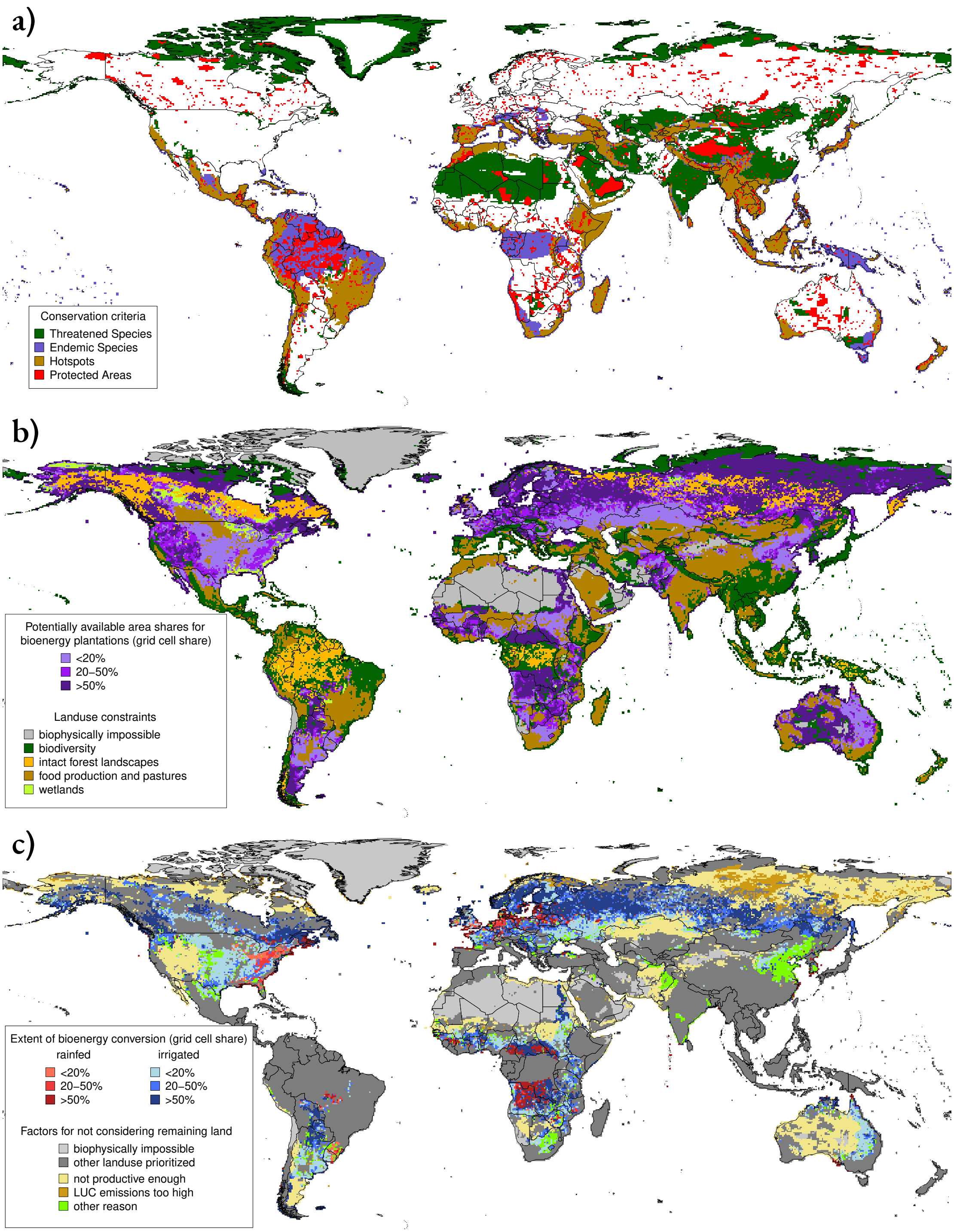


Figure 4.1: a) Areas excluded from conversion to BPs due to biodiversity and conservation criteria: Biodiversity hotspots (Mittermeier et al., 2011), World Database on Protected Areas (UNEP-WCMC, 2018), endemic species (Kier et al., 2009), threatened species (Pimm et al., 2014) **b)** Potential BP fractional area (%) outside of regions covered by cropland and pastures, or regions protected for reasons of biodiversity (see a and Methods for detailed description). **c)** Mean 2090-2099 fractional areas for rainfed (red) and irrigated (blue) BP assumed in scenario WM and parameter set IrrExp; together with factors for not considering BPs in remaining potentially available areas shown in b).

The irrigation module accounts for three irrigation techniques: surface, sprinkler, and drip (Jägermeyr et al., 2015), with different supply efficiencies. Water use for household, industry, and livestock (HIL) (Flörke et al., 2013) is prescribed. Additionally, water management strategies such as mulching, water harvesting, and conservation tillage are represented for cropland and, newly in this study, for BPs as well, following (Jägermeyr et al., 2016) by adapting the parameters (reduced soil evaporation of 50 %, local storage capacity of 200 mm, collected on 50 % of the managed areas, irrigation if soil moisture <40 % of field capacity, and optimized soil infiltration) for BPs.

We forced the LPJmL model with monthly climate data (1901–2100) from the PanClim dataset (Heinke et al., 2013) consistent with a 1.5 °C trajectory in 2100 with a slight temperature overshoot; with soil texture data (Nachtergaele et al., 2009), and with land-use patterns (prescribed agriculture from Fader et al. (2010), and BPs as per scenario). Since the target variables in this study (freshwater withdrawals, BP area, carbon sequestration) are much more sensitive to the individual parameter setups than to the actual climate input (forcing LPJmL with output from other climate models changed global BP water consumption by ±4 %; data not shown), we force the model with only one climate model (MPI-ECHAM5). Simulations are performed with an initial spin-up of 5010 years of potential natural vegetation (recycling the first 30 years of climate input) to bring global carbon pools to an equilibrium, followed by 316 years of transient spin-up using historic land-use patterns from 1700 to 2015. The food crop land-use pattern from 2015 is kept constant for the remainder of the 21st century. BP plantations are assumed to not be implemented before 2030.

Total annual water withdrawals in every grid cell are computed as the sum of applied irrigation water as well as drainage and evaporative conveyance losses and withdrawals for HIL. Water consumption is computed as the sum of applied irrigation water, evaporative conveyance losses, and HIL consumption minus return flows from applied irrigation water. Attribution of consumption and withdrawal to BPs is obtained through computing the cell-wise difference between withdrawals in the run with BPs and the reference simulation without.

4.4 Results

The projected total global freshwater withdrawals (2090-2099) exhibit a large range between 2,619 and 5,998 $km^3\,yr^{-1}$, with a BP contribution of 387–3,167 $km^3\,yr^{-1}$ (see Table 4.2 for tabled simulation data). The baseline scenario without BPs reaches ~3,000 $km^3\,yr^{-1}$ for the same period. Adding BP with unrestrained withdrawals (IrrExp – IRR) almost doubles the total withdrawals compared to purely rainfed BPs. By respecting EFRs and applying improved water management (EFR and WM), the total global water withdrawals can be kept below 4,000 (3,000) $km^3\,yr^{-1}$ in IrrExp (TechUp). Note that despite non-negligible withdrawals for BPs in the order of 400 $km^3\,yr^{-1}$ in scenario WM of setups Basic and TechUp, the total withdrawals may even fall below those of the respective RF scenario (3,011 km^3 yr^{-1}), because EFRs are taken into account also for withdrawals of agricultural irrigation and because water is assumed to be more effectively managed also on cropland. Total global (food) crop yields are not substantially changing for RF and IRR compared to a reference run without BP. They are reduced by 3.5 % in EFR, while in WM the water and soil management results in 8.4 % higher crop yields than in RF.

We observe that most of the scenarios do not reach the target sequestration, meaning that from a certain year on, no more additional BP area is available that fulfils the respective scenario requirements. The dedicated freshwater withdrawals for irrigation of BPs needed to provide 255 Gt C of NEs range from 416 km^3 yr^{-1} (TechUp - WM) to 2,388 km^3 yr^{-1} (IrrExp - IRR).

In the Basic scenarios RF, IRR, EFR, and WM (Figure 4.2, bottom centre), total NEs from BPs are not fulfilling the sequestration target of 255 Gt C. The RF scenario reaches 170 GtC (with no additional water use on top of the global non-BP water use of currently 3,011 km^3 yr^{-1}). Irrigation of BPs (unconstrained by EFRs) with 701 km^3 yr^{-1} (2090-2099 mean) increases this value to 217 GtC (IRR). With stringent environmental flow protection (EFR) the water demand is reduced to 400 km^3 yr^{-1}, whereby a total sequestration of only 181 GtC is achievable. Additional water management strategies (WM) slightly increases the sequestration to 195 GtC while staying below the irrigation water demand of EFR (387 km^3 yr^{-1}).

To possibly increase the carbon sequestration, we considered either irrigation expansion or technology upgrades. An increase of irr_{frac} from 0.33 to 1.0 (Figure 4.2, bottom right) enables scenario IRR to reach the sequestration goal and WM to almost reach it (243 GtC). These gains, however, come at the cost of strongly increased water withdrawals for the BPs. IRR more than triples the demand for BP irrigation to 2,388 km^3 yr^{-1}, while in the WM scenario, more than four times more irrigation water is used (1,742 km^3 yr^{-1}) compared to Basic. In the EFR scenario, less water compared to WM is used (1,474 km^3 yr^{-1}), however, for a lower sequestration amount. In the TechUp setup (Figure 4.2, bottom left), in which c_{eff} is increased from 50 % to 70 %, the additional carbon that can be sequestered from the raw yields is enough to fulfil the sequestration target of 255 Gt C in all four scenarios (RF, IRR, EFR, WM). As a beneficial effect, the associated freshwater withdrawals for BP irrigation are comparable to those of the Basic setup (IRR, 638 km^3 yr^{-1}; EFR, 417 km^3 yr^{-1}; WM, 416 km^3 yr^{-1}).

The higher sequestration demand of 355 Gt C, which could become necessary due to delayed or failed mitigation, was analysed in the TechUp355 (top left) and IrrExp355 setups (top right). None of the scenarios, however, can deliver sequestrations that high. The IRR scenarios come the closest, although they neglect the EFRs (337 GtC / 775 km^3 yr^{-1} for TechUp355 and 321 GtC / 3,167 km^3 yr^{-1} for IrrExp355).

For scenarios that reach the sequestration goal (Figure 4.3) with restricted irrigation use (TechUP - RF, IRR, EFR, and WM) the majority of irrigated BPs is situated in higher latitudes, namely Canada, Scandinavia, and Russia (due to the preference for cells with a low water/productivity ratio), while areas of highest productivity (Figure B2.2) and highest LUC emissions (Figure B2.2) are in the tropics. The biophysical limitations allow the productive growth of herbaceous bioenergy plants only in latitudes between $-40°$ and $50°$. Due to their plant physiology, woody bioenergy plants have significantly lower yield productivities, but are able to grow in sub-polar regions. The optimization scheme also simulates plantation of bioenergy trees in the tropics, which are either chosen for their greater net carbon sequestration or their lesser need for irrigation.

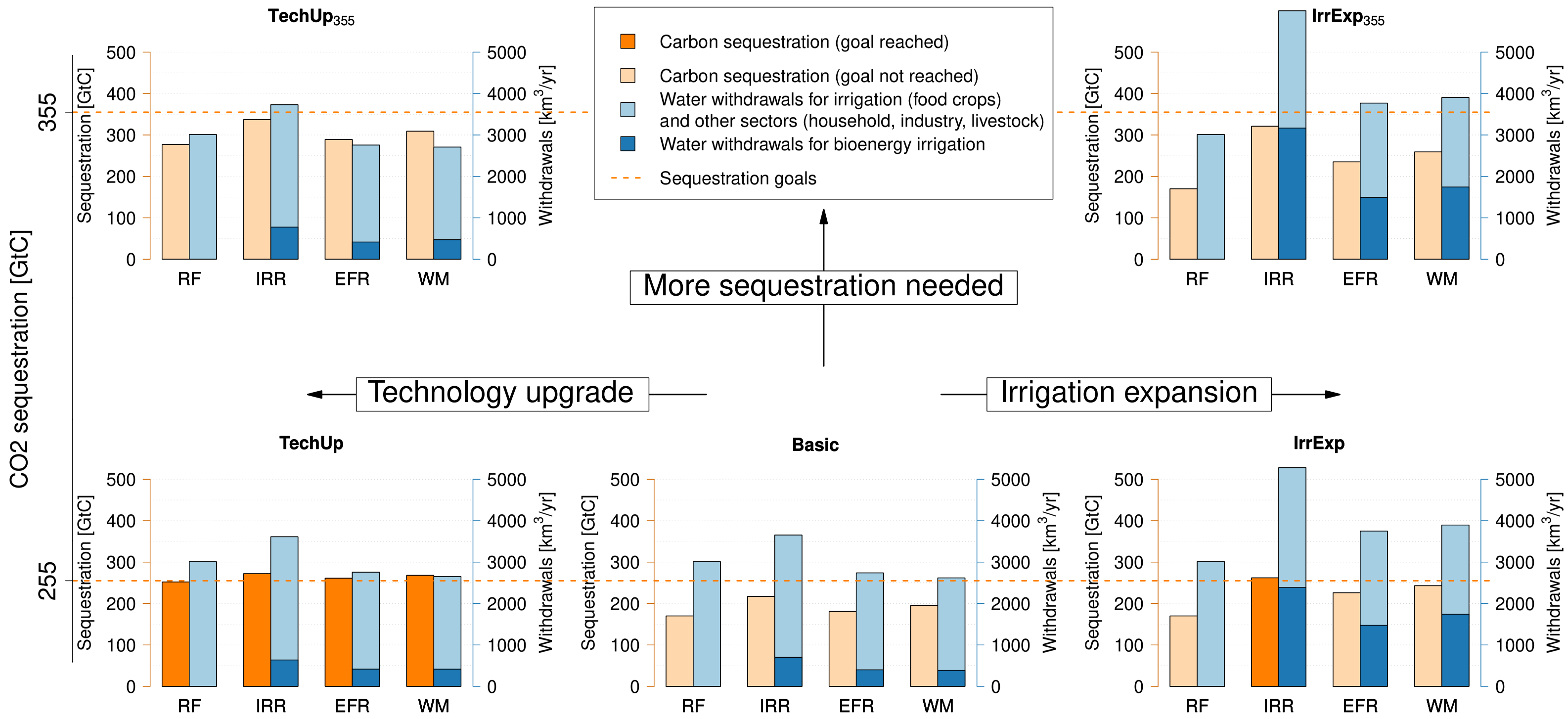


Figure 4.2: Total global carbon sequestration (2030–2100) and yearly freshwater withdrawals (mean 2090–2099) including withdrawals for agriculture and HIL for the four scenarios in five different parameter setups. Basic, c_{eff} =50 % and irr_{frac} =0.33; IrrExp, same but irr_{frac} =1.0; TechUp, same as Basic but c_{eff} =70 %. The upper panel ("more sequestration") refers to an increased sequestration target of 355 Gt C instead of 255 Gt C. RF - rainfed, IRR - unconstrained withdrawals, EFR - respect Environmental Flow Requirements, WM - water management (see also Table 4.1).

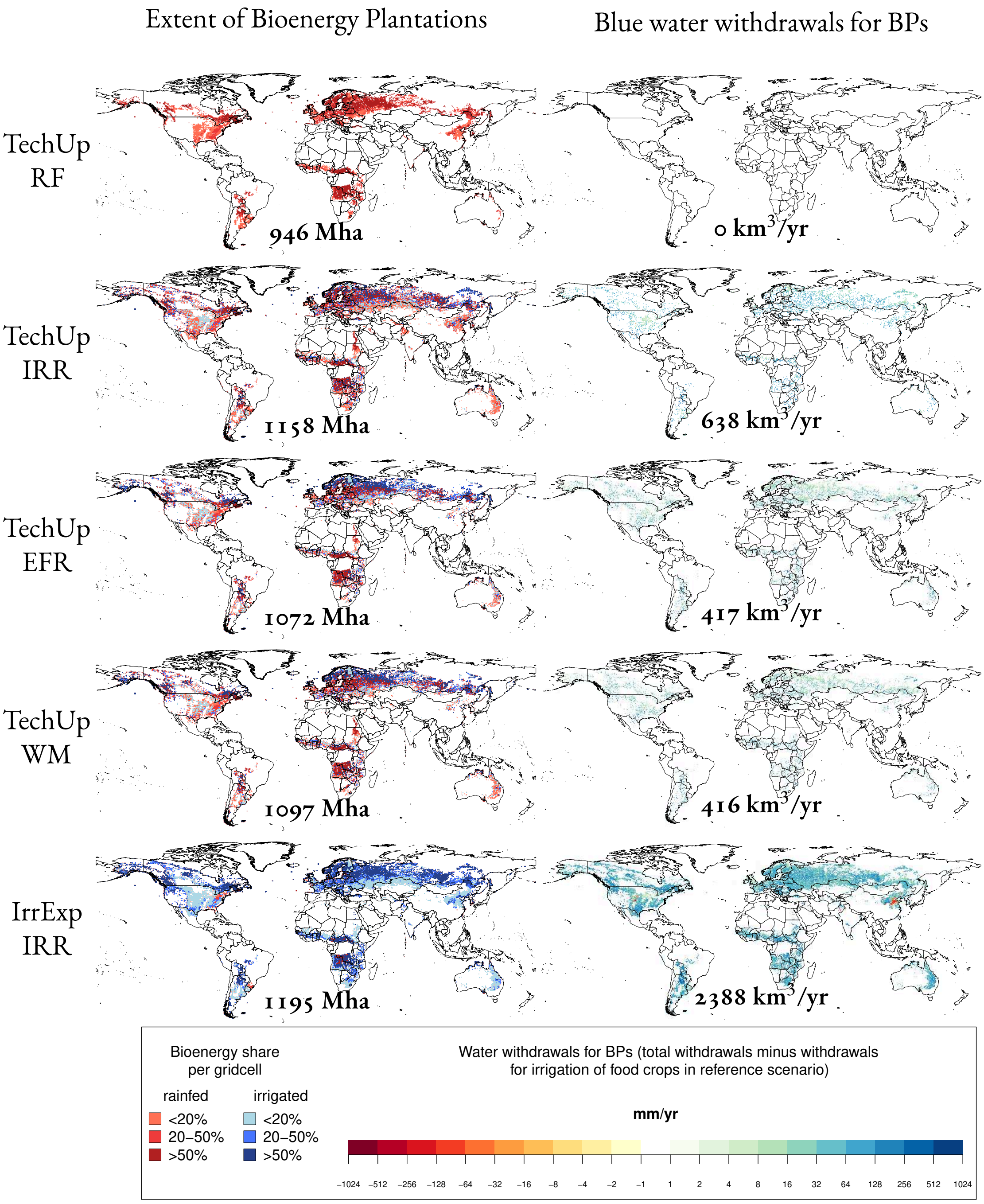


Figure 4.3: Mean 2090-2099 fractional areas for rainfed (red) and irrigated (blue) BPs – left panel –, and water withdrawals for irrigation of BPs (computed as difference of total withdrawals minus withdrawals from food-crops-only reference run) – right panel – displayed for all scenarios that fulfil the sequestration target of 255 Gt C. Attributed blue water withdrawals can be negative, if the respective scenario withdraws less water than the reference run. This can happen for cells, where addition of BPs changes local ET-fluxes, or new upstream irrigation reduces discharges below EFRs.

Table 4.2: Global model results for simulations included in Figure 4.2.

Basic	**unit**	**RF**	**IRR**	**EFR**	**WM**
Sequestration	Gt C	225	263	229	246
Net Sequestration ($Seq - LUC$)	Gt C	170	217	181	195
Total BECCS yield	Gt C	450	525	458	491
Rainfed BP yield	Gt C	403	337	284	308
Total BP area	Mha	1,036	1,416	1,177	1,247
Only woody BP area	Mha	725	1,047	881	927
Total withdrawals	$km^3\,yr^{-1}$	3,011	3,653	2,739	2,619
BP withdrawals	$km^3\,yr^{-1}$	0	701	400	387
Total blue water consumption	$km^3\,yr^{-1}$	1,160	1,782	1,237	1,144
BP blue water consumption	$km^3\,yr^{-1}$	0	642	361	351

IrrExp	**unit**	**RF**	**IRR**	**EFR**	**WM**
Sequestration	Gt C	225	275	258	278
Net Sequestration ($Seq - LUC$)	Gt C	170	262	226	243
Total BECCS yield	Gt C	450	550	517	556
Rainfed BP yield	Gt C	403	58	121	118
Total BP area	Mha	1,036	1,195	1,164	1,215
Only woody BP area	Mha	725	1,001	909	927
Total withdrawals	$km^3\,yr^{-1}$	3,011	5,280	3,749	3,895
BP withdrawals	$km^3\,yr^{-1}$	0	2,388	1,474	1,742
Total blue water consumption	$km^3\,yr^{-1}$	1,160	3,358	2,216	2,313
BP blue water consumption	$km^3\,yr^{-1}$	0	2,239	1,368	1,553

TechUp	**unit**	**RF**	**IRR**	**EFR**	**WM**
Sequestration	Gt C	318	326	320	326
Net Sequestration ($Seq - LUC$)	Gt C	252	272	261	268
Total BECCS yield	Gt C	455	466	457	466
Rainfed BP yield	Gt C	388	282	270	275
Total BP area	Mha	946	1,158	1,072	1,097
Only woody BP area	Mha	570	821	738	779
Total withdrawals	$km^3\,yr^{-1}$	3,011	3,612	2,755	2,654
BP withdrawals	$km^3\,yr^{-1}$	0	638	417	416
Total blue water consumption	$km^3\,yr^{-1}$	1,160	1,735	1,258	1,173
BP blue water consumption	$km^3\,yr^{-1}$	0	587	383	378

IrrExp355	**unit**	**RF**	**IRR**	**EFR**	**WM**
Sequestration	Gt C	224	330	268	294
Net Sequestration ($Seq - LUC$)	Gt C	170	321	235	259
Total BECCS yield	Gt C	447	659	535	587
Rainfed BP yield	Gt C	414	63	127	127
Total BP area	Mha	1,069	1,377	1,198	1,262
Only woody BP area	Mha	750	1,105	920	937
Total withdrawals	$km^3\,yr^{-1}$	3,010	5,998	3,768	3,903
BP withdrawals	$km^3\,yr^{-1}$	0	3,167	1,493	1,744
Total blue water consumption	$km^3\,yr^{-1}$	1,160	4,041	2,227	2,324
BP blue water consumption	$km^3\,yr^{-1}$	0	2,946	1,379	1,561

TechUp355	**unit**	**RF**	**IRR**	**EFR**	**WM**
Sequestration	Gt C	344	396	349	370
Net Sequestration ($Seq - LUC$)	Gt C	277	337	289	309
Total BECCS yield	Gt C	492	566	498	529
Rainfed BP yield	Gt C	436	357	309	326
Total BP area	Mha	1,055	1,396	1,179	1,237
Only woody BP area	Mha	629	906	772	823
Total withdrawals	$km^3\,yr^{-1}$	3,011	3,731	2,756	2,707
BP withdrawals	$km^3\,yr^{-1}$	0	775	415	473
Total blue water consumption	$km^3\,yr^{-1}$	1,160	1,847	1,254	1,213
BP blue water consumption	$km^3\,yr^{-1}$	0	706	378	419

4.5 Discussion

This study was designed to estimate the biophysical potential and water requirements for BECCS if being applied as the primary NET for fulfilling the 1.5 °C target. This approach to model BECCS is based on explicit modeling of BPs (and the associated emissions from land-use change in the process of plantation allocation) together with an assumed carbon conversion efficiency. We thereby adopt an Earth System perspective based on the planet's biophysical capacity and especially the trade-offs associated with freshwater availability and management, rather than explicitly addressing economic feasibility. We have not considered the logistics and economics of transport of solid biofuels, nor the costs of CCS (e.g. Tauro et al. 2018; Strefler et al. 2018) as these were beyond the scope of our research. We acknowledge that these issues will be important for the feasibility of strategies for BECCS, not least because the areas identified having the greatest potential for BPs are far from areas of greatest energy demand. However, if these constraints were considered additionally in a more comprehensive study, NE potentials may not necessarily be lower but the BP area would most likely be simulated to shift to other regions (see Bonsch et al. 2016).

The key finding is that NE demands necessary to limit global warming to 1.5 °C cannot be met by BECCS alone due to freshwater limitations (and under the land available for conversion assumed here), except under the most ambitious assumptions about conversion efficiency or water use. The only scenario not relying on a high carbon conversion efficiency of 70 % is a scenario without respecting EFRs, which thus would come at the cost of riverine ecosystems and overall environmental sustainability. Safeguarding EFRs in turn, would largely limit the irrigation-sustained NE potential. These results add new evidence to the discussion that pathways towards higher water use efficiencies and carbon conversion efficiencies need to be prioritized to meet targeted NEs. The projected additional freshwater withdrawals for achieving the 1.5 degree target using BECCS as the primary NET (Figure 4.2) are substantial (up to 2,400 $km^3\,yr^{-1}$ – mean 2090-2099) and could thus reach the order of current global water withdrawals. Correspondingly, the total water consumption across all sectors would rise to above 3,300 $km^3\,yr^{-1}$ (Figure B2.3), thereby possibly transgressing the "planetary boundary" for freshwater use (currently set at a total human consumption of $2,800$ or 4,000 $km^3\,yr^{-1}$, respectively; Gerten et al. 2013a; Steffen et al. 2015), with associated detrimental effects for the Earth system. In comparison with previous water consumption estimates for BPs, as for instance in Beringer et al. (2011) (1,481–3,880 $km^3\,yr^{-1}$), Bonsch et al. (2016) (3,000–6,000 $km^3\,yr^{-1}$), or Jans et al. (2018) (1,500–5,000 $km^3\,yr^{-1}$), our global estimates exhibit a similar to larger span while being somewhat more conservative in absolute terms (351–2,946 $km^3\,yr^{-1}$) due to the large range of scenarios considered and other divergent assumptions such as on the potential locations for BPs in particular. Our study thus does not constrain the previous range but provides a systematic exploration of underlying causes (water use limitations, environmental constraints, management options).

Thus, it is important to note for our study as well that the global amount of freshwater requirements strongly depends on the underlying assumptions about conversion efficiency, water management, and EFR protection. Most freshwater is simulated to be consumed in the IrrExp scenario, whereas the Basic and TechUp scenarios involve significantly lower water consumption. Naturally, among the water use scenarios of each parameter setup, IRR always leads to highest water consumption, while EFR and WM show lower values due to their strict water allocation scheme (EFR) and the constrained water use (WM), respectively.

Our results indicate that a targeted NE amount of 255 Gt C (between 2030 and 2100) could be produced under rainfed conditions only if high conversion efficiencies would apply (c_{eff} $\geq$70 %). Even under this condition, though, rainfed BPs would not provide enough biomass for possible higher NE demands up to the here considered 355 Gt C, which may become necessary if climate change mitigation efforts fail or slow down. The Basic setup cannot provide enough NE to fulfill the sequestration demand of even the lower target (255 Gt C), suggesting that either irrigation expansion or highly efficient BECCS systems exceeding 50 % carbon conversion efficiency will be needed (or a combination of both). It appears unlikely to implement such high efficiencies at the global level within the next decades due to multiple obstacles such as a lack of socio-political acceptance, policy incentives, and technological readiness Fuss et al. (2014); Vaughan et al. (2018); Fridahl and Lehtveer (2018); Gough et al. (2018); Reiner (2016).

In view of these technical and institutional challenges, productivity improvements supported by irrigation expansion come into focus for near-term solutions. It is clear that additional water withdrawals at the level presented here would be associated with severe environmental degradation (at least in scenarios where EFRs are not respected) or increased water stress (Hejazi et al., 2015; Rockström et al., 2014). While such obstacles require further systematic study, any sustainable implementation of BECCS requires serious consideration of freshwater issues in the form of rigid environmental protection, water legislation, and water management improvements.

In addition to the water requirements for irrigation, BPs need extensive land areas (for further discussion see Boysen et al. 2016; Heck et al. 2016b; Werner et al. 2018). In our study, the maximum additional arable area for BPs under rainfed conditions is roughly 1,000 Mha. Irrigation makes more grid cells (200–400 Mha) productive enough to cross the minimum yield threshold and compensate for LUC emissions (see Figure B2.2). The yield threshold is the lower limit of what is considered economically feasible today, while both yields and the threshold may change in the future (even though they are already quite optimal parameters) due to e.g. genetic optimization and management. The assumption that BPs would only be planted if LUC emissions are at least twice compensated for by the net sequestration amount is strict, but economically justified. Conversely, irrigation makes BPs in many regions more productive, such that per unit of NEs, less land is needed. This can be understood as a trade-off between water and land, which has been described before (Bonsch et al., 2016; Jans et al., 2018).

However, large portions of the identified potentially available areas for BPs in this study are recreational areas or wild remote landscapes which are already in a state of increasing risk for biodiversity loss (Steffen et al., 2015). Given that the scenarios suggest replacement of e.g. larger fractions of boreal forest in Scandinavia and northern Asia, which is unlikely to occur in reality at such large scale, our estimates appear to be on the conservative side. If those areas would not be released for conversion, larger BP areas, or more intense irrigation, would have to take place elsewhere to achieve a similar amount of NEs, probably involving even stronger pressure on freshwater systems there. Thus, we stress that the here simulated spatial BP patterns are to be interpreted as biophysical maximum potentials derived under strict conservation criteria, distributed and optimized globally according to the water use efficiency. Further analysis could evaluate the wider consequences of ecosystem change (e.g. terrestrial and aquatic biodiversity loss through conversion of natural land to BPs), like Ostberg et al. (2018) provide for biospheric change under scenarios designed to sustain Paris mitigation efforts.

Additionally, competition for water between irrigated agriculture and BPs could be explicitly studied by e.g. exploring scenarios where the irrigation of crops always has the highest priority.

In sum, we find that second-generation bioenergy combined with CCS alone can deliver sufficient NEs for ambitious climate targets only under highly optimized conditions and with potentially detrimental side effects on freshwater ecosystems. This first benchmark quantification merits more detailed follow-up studies, especially to analyse synergies and trade-offs with additional NETs operating in different domains, in a complex modelling framework. However, according to initial studies, other NETs would come along with environmental side-effects too, for example with respect to the area demand of afforestation or the water demand of Direct-Air-Capture (Smith et al., 2016).

4.6 Conclusion

Despite the socio-political and technological barriers to the implementation of BECCS, bioenergy will most likely become more relevant as a substitution for fossil energy with the need to convert large areas to BPs. To increase the yields and thus reduce the pressure on land, these plantations might have to be irrigated to a substantial degree, potentially putting many freshwater systems under severe additional pressure. Therefore, local water policies, such as for safeguarding EFRs, are important tools to sustain the integrity of freshwater ecosystems. We show that there is a trade-off between limiting irrigation on BPs to sustain EFRs and attaining levels of NEs likely required for limiting global warming to 1.5 °C. On-field water and soil management can help reducing this water gap for BPs and for agriculture. Nevertheless, a stringent and fast reduction of CO_2 emissions is inevitable, because higher carbon sequestration demands would have profound impacts on freshwater systems and their ecological functions that are fundamental to life and societies.

4.7 Acknowledgements

The authors declare no conflict of interest. This study was funded by the CE-Land+ project of the German Research Foundation's priority program DFG SPP 1689 on "Climate Engineering – Risks, Challenges and Opportunities?", by the BMBF project BioCAP-CCS (grant no. 01LS1620B) and with partial support from the University of Chicago Center for Robust Decision-making on Climate and Energy Policy (NSF grant #SES-146364). We thank Sibyll Schaphoff, Jens Heinke, Wolfgang Lucht, and Sebastian Ostberg for valuable discussions, as well as two anonymous reviewers for their constructive comments.

5

Irrigation of biomass plantations may globally increase water stress more than climate change

An edited version of this chapter has been published in the journal Nature Communications:

Stenzel, F., P. Greve, W. Lucht, S. Tramberend, Y. Wada, and D. Gerten. Irrigation of biomass plantations may globally increase water stress more than climate change. *Nature Communications*, 12:1512, 2021b. https://doi.org/10.1038/s41467-021-21640-3

5.1 Abstract

Bioenergy with carbon capture and storage (BECCS) is considered an important negative emissions (NEs) technology, but might involve substantial irrigation on biomass plantations. Potential water stress resulting from the additional withdrawals warrants evaluation against the avoided climate change impact. Here we quantitatively assess potential side effects of BECCS with respect to water stress by disentangling the associated drivers (irrigated biomass plantations, climate, land-use patterns) using comprehensive global model simulations. By considering a widespread use of irrigated biomass plantations, global warming by the end of the 21st century could be limited to 1.5 °C compared to a climate change scenario with 3 °C. However, our results suggest that both the global area and population living under severe water stress in the BECCS scenario would double compared to today and even exceed the impact of climate change. Such side effects of achieving substantial NEs would come as an extra pressure in an already water-stressed world and could only be avoided if sustainable water management would be implemented globally.

5.2 Introduction

The Earth system is facing multiple environmental pressures (e.g. climate change, water shortages, ecosystem degradation), while the need remains to ensure food and water security for a growing world population. Additionally, there is growing interest in NE technologies linked to the desire to achieve the 1.5 °C target without jeopardizing sustainable development goals (SDGs) such as achieving water security. These challenges and their prospective solutions are intrinsically coupled, requiring strong trade-offs to be resolved. One of these dilemmas is centred around freshwater availability and stress. Water stress - affecting about 1.4–4 bn people already depending on the chosen metric (Smakhtin et al., 2004; Kummu et al., 2010; Gosling and Arnell, 2016; Mekonnen and Hoekstra, 2016) - may strongly increase in the future not only due to population growth, but also due to impacts of global climate change (Hoekstra et al., 2012; Schewe et al., 2014; Wada et al., 2016; Heinke et al., 2019). For example, a further 8 % of world population may be exposed to increasing water stress due to climate change alone (Gerten et al., 2013b). While mitigation of climate change will thus be imperative to reduce the pressure on freshwater resources (among other benefits) (Rockström et al., 2016), the currently pledged emission reductions may not be enough to limit mean global warming to below 2 °C as envisaged in the Paris Agreement (Luderer et al., 2013; Rogelj et al., 2018), requiring further measures such as active plant-based CO_2 sequestration from the atmosphere through dedicated biomass plantations combined with carbon capture and storage (BECCS) (Minx et al., 2018; Klein et al., 2014; Gasser et al., 2015). BECCS is based on the cultivation of fast growing plant species, which are assumed to be regularly harvested for their biomass and subsequently processed to biofuels (replacing liquid fossil energy carriers), or burned for energy generation (offsetting coal or gas power plants), while the released

CO_2 is (at least partially) captured (Azar et al., 2006; Caldeira et al., 2013). Thus the whole process would remove CO_2 from the atmosphere and counteract anthropogenic greenhouse gas emissions to reduce climate change. The sequestration potential was estimated to be 0.1–2 GtC yr^{-1} by 2050 and 0.3–3.3 GtC yr^{-1} by 2100 (Lenton, 2010; Smith et al., 2016). Utilization of biomass is supposed to provide substantial amounts of electric energy or liquid fuels (up to 500 EJ yr^{-1}), and is thus assumed to be deployed at large-scale (even without providing negative emissions via CCS) and also rather early in the 21^{st} century (together with afforestation) in contrast to more expensive NE technologies like direct air capture (Bauer et al., 2018).

However, at the large-scale required, biomass production is likely to increase the pressure along multiple environmental dimensions locally and globally (Boysen et al., 2016; Fuss et al., 2018; Heck et al., 2018), including increased competition for scarce freshwater resources to the extent that such plantations require irrigation in order to reach anticipated sequestration levels (Beringer et al., 2011; Yamagata et al., 2018). From a sustainability perspective, it is important to understand how additional water use for bioenergy production affects water stress in relation to the avoided change that would occur in a warming world without irrigated biomass plantations.

We define water stress using an established globally applicable metric: the local ratio of total human water withdrawals to available discharge (Raskin et al., 1997; Alcamo et al., 2003; Gosling and Arnell, 2016), from which the yearly mean water stress is derived.

To corroborate findings from one earlier regional study that suggested the water stress in a mitigation scenario based on irrigated bioenergy may indeed supersede that of unabated climate change (Hejazi et al., 2015), we here provide a systematic global-scale analysis comparing water stress in two plausible future scenarios: A world with strong mitigation including (partially irrigated) bioenergy plantations ($\sim$600 Mha in 2095) as a contribution to limit mean global warming by the end of the century to around 1.5 °C (hereinafter referred to as scenario *BECCS*), and one with only marginal extent of bioenergy plantations ($\sim$30 Mha in 2095) resulting in warming of 3 °C (*CC*).

We thus advance earlier studies (Hejazi et al., 2014, 2015; Hu et al., 2020) by globally and spatially explicitly comparing water stress and its drivers between a strong climate change scenario with one where bioenergy is used for mitigation. We take into account available surface water restrictions (e.g. to safeguard environmental flow requirements of river ecosystems) for irrigation of biomass plantations and cropland. This approach enables us to highlight and quantify trade-offs regarding different levels of water protection, impacts of climate change versus mitigation through BECCS, and also the possible contribution of improved water management to help solve this dilemma. Unlike previous BECCS water demand studies (Jans et al., 2018; Stenzel et al., 2019), we apply transient land-use projections for both bioenergy and food crops (Frieler et al., 2017), which are consistent with future pathways of green house gas emissions and socio-economic development.

The scenarios are based on data from the Representative Concentration Pathways RCP2.6 (*BECCS*)

Table 5.1: Scenario overview. Climate, land use, and water use input data for 4 GCMs (all based on SSP2) is used from the ISIMIP2b project (Frieler et al., 2017). The irrigation fraction is obtained from a sensitivity analysis as part of this study. Sustainable water management is a combination of withdrawal restrictions based on EFRs (Pastor et al., 2014), local water storage, and improved on-field irrigation efficiencies (Jägermeyr et al., 2016; Stenzel et al., 2019).

Scenario	**CC**	**BECCS**	**BECCS+SWM**
Climate forcing	RCP6.0	RCP2.6	RCP2.6
Biomass plantation area (2090-2099)	30 Mha	600 Mha	600 Mha
of which equipped for irrigation	30 %	30 %	45 %
Sustainable water management	no	no	yes

and RCP6.0 (*CC*), both following the "middle of the road" narrative of the Shared Socioeconomic Pathway SSP2, provided by the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b) (Frieler et al., 2017). Scenarios differ in terms of the degree of climate change, BECCS deployment, and land-use change trajectories over the 21st century including differences in the spatial distribution of (rainfed and irrigated) areas with agricultural crops and biomass plantations (Table 5.1).

To study the beneficial effects of more sustainable water use policies while providing the same amount of biomass as in scenario *BECCS*, we additionally explore a scenario with irrigated bioenergy plantations that are accompanied by sustainable water management (*BECCS+SWM*), while all other parameters are chosen for maximum consistency with scenario *BECCS*. This scenario assumes the preservation of environmental flow requirements (EFRs) and implements advanced on-field water management (Jägermeyr et al., 2016; Stenzel et al., 2019) on both agricultural and bioenergy sites. EFRs determine a percentage of pristine, undisturbed mean monthly river flow, here following the variable monthly flow (VMF) method (Pastor et al., 2014).

Fractions of the local biomass plantation area that are equipped for irrigation (30 % – *BECCS*, 45 % – *BECCS+SWM*) are obtained from a sensitivity analysis, assuming that 50 % of the required harvest increase between the *Baseline* and the ISIMIP2b harvests including technological change is achieved by irrigation (for more details see Methods – Determining the bioenergy irrigation amount).

The simulations are performed using the process based global vegetation and water balance model LPJmL (Schaphoff et al., 2018b) forced by climate change scenarios from four General Circulation Models (GCMs) selected in the ISIMIP2b project: HadGEM2-ES, MIROC5, GFDL-ESM2M, IPSL-CM5A-LR. We use an ensemble of GCMs to account for the remaining variation in precipitation projections inherent to GCMs, even when forced with the same RCP (IPCC, 2013; Woldemeskel et al., 2016).

We compute the water stress index (WSI) for each 0.5 x 0.5 degree grid cell as monthly averages of the present period 2006 to 2015 (*Today*) and the future period 2090 to 2099, expressed as percentages of human water use (withdrawals for households, industry, and irrigation of biomass plantations and cropland) compared to total discharge. High stress is assumed to prevail in cells where the yearly mean WSI>40 % (Raskin et al., 1997; Vörösmarty et al., 2000) (for more details see Methods – Water stress index WSI). From these cells, we calculate sums of global area as well as population under high water stress.

Here, we show that both the global area and the population exposed to high water stress would double in the *BECCS* scenario compared to today and even exceed the impact of climate change (scenario *CC*), unless sustainable water management was in place to reduce the pressure on freshwater resources.

5.3 Results

5.3.1 Globally aggregated results

We find that by the end of this century (2090-2099), the global population and land area under high water stress will increase sharply in all scenarios without sustainable water management compared to the present (2006-2015). The total land area under high water stress – currently 1,023 (982–1,065) Mha – is simulated to increase in the inter-model mean to 1,580 (1,520–1,613) Mha in *CC* and 1,928 (1,901–1,970) Mha in *BECCS*. The number of people experiencing high water stress – currently 2.28 (2.23–2.32) billion people – increases to 4.15 (4.03–4.24) billion in *CC* and 4.58 (4.46–4.71) billion in *BECCS* (Figure 5.1, Table S1).

Increases for population under high water stress include the effect of increased world population from 7 billion people in 2010 to 9 billion in 2100 according to SSP2 (KC and Lutz, 2017).

5.3.2 Global distribution of water stress

In the following we focus the presentation of results on simulations under HadGEM2-ES climate projections, which represents an intermediate model response to the applied emission scenario among the group of four GCMs (compare Figure C3.1 and Figure C3.2). For results for all other GCMs we refer to the supplementary material (Figure C3.4, Figure C3.5, Figure C3.6, Figure C3.7,Figure C3.8, Figure C3.9).

The spatial distribution of locations with high water stress in the *CC* scenario is broadly similar to today's patterns, but the total area affected as well as the local WSI values increase significantly (Figure 5.2), indicating that water stress in current hotspots will persist or even increase. Regional hotspots of WSI increases include the Mediterranean, the Middle East, India, North-East China, and South-East and southern West-Africa (Figure C3.10). In the *BECCS* scenario high water stress extends to otherwise unaffected regions (not highly stressed *Today* nor in *CC*) e.g. the East of Brazil

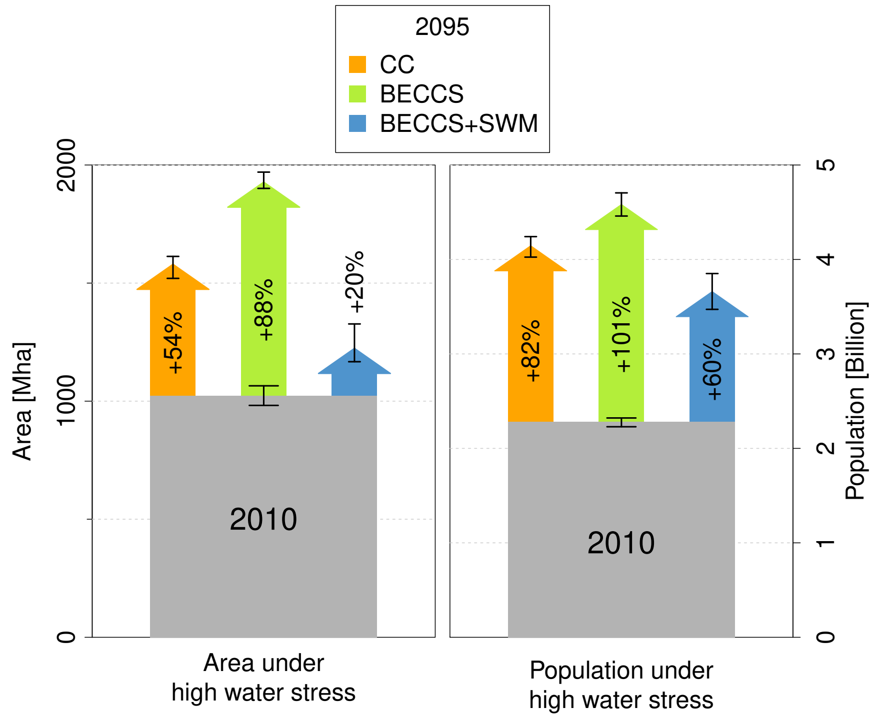


Figure 5.1: Simulated increase of area and population exposed to high water stress from 2010 (2006-2015) to 2095 (2090-2099) in the different scenarios: CC (climate change), BECCS (bioenergy with carbon capture and storage), BECCS+SWM (BECCS with sustainable water management). The numbers represent global sums of grid cell-level area and population, respectively, where annual mean WSI>40 %. Shown are the mean change and the ranges resulting from the differences in climate simulations based on the four GCMs. Grey bars represent the current (2006-2015 average) levels.

and large parts of Sub-Saharan Africa (Figure 5.2, Figure C3.11). These are regions where large-scale biomass plantations are assumed (according to the respective ISIMIP2b land-use scenario for RCP2.6, see Methods – Determining the bioenergy irrigation amount) and in which additional irrigation may therefore be required to increase biomass yields.

5.3.3 Water stress differences between scenarios

All future scenarios exhibit similar or higher water stress almost everywhere compared to *Today*, with only the Western United States and some locations in Asia showing the opposite behaviour (Figure C3.10, Figure C3.11).

Globally, an area of about 2,400 Mha (about 16 % of the total land surface area) shows a difference larger than ±10 % in WSI between the *BECCS* and *CC* scenarios. More than two-third (72 %) of this area exhibits a higher WSI in the *BECCS* scenario (Figure 5.3a), mostly located in Central and South

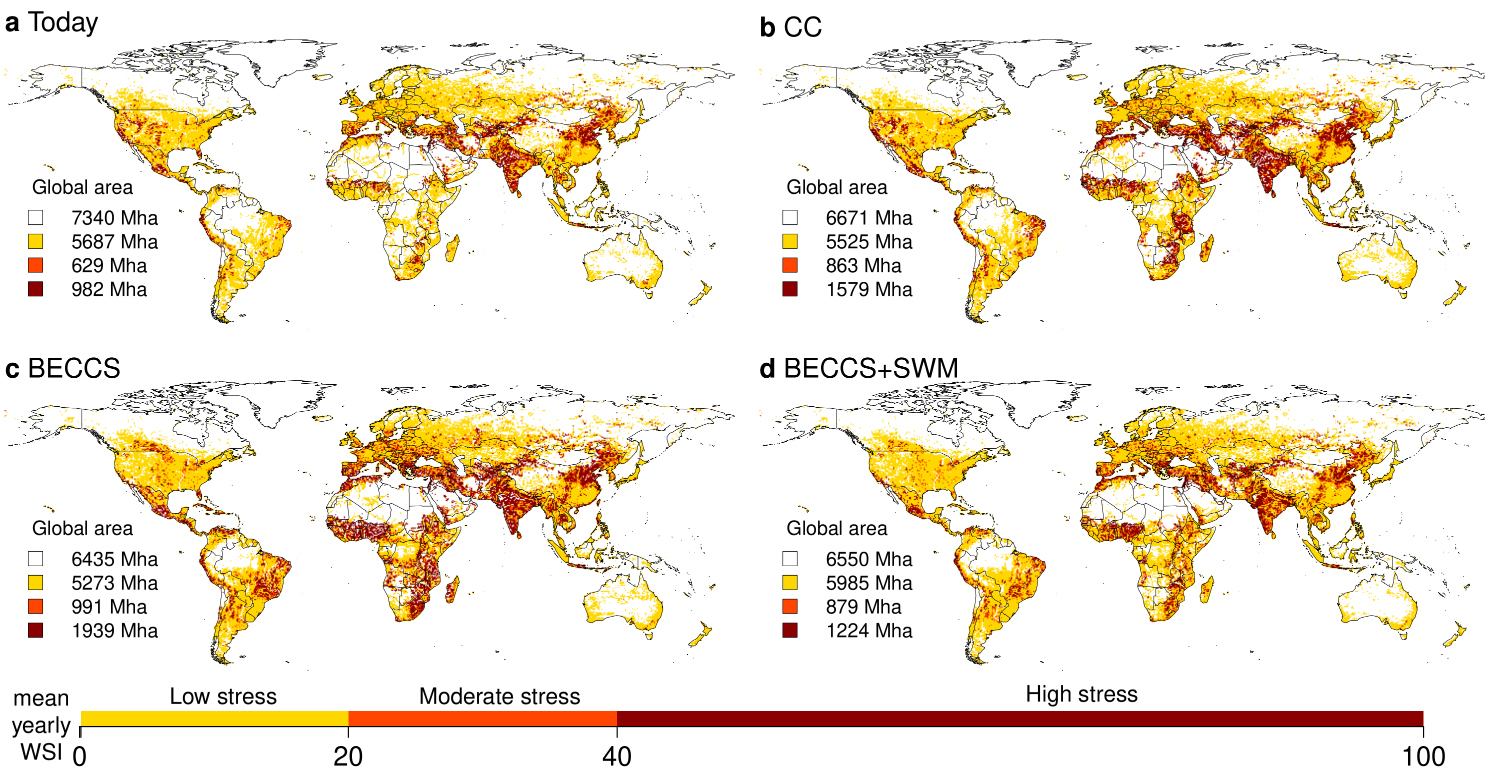


Figure 5.2: WSI simulated under HadGEM2-ES climate forcing for *Today* (2006-2015), and for future scenarios (2090-2099) *BECCS*, *CC*, *BECCS+SWM*. The global numbers refer to the total area exposed to the different degrees of water stress: $(0\text{–}0.1)$ % (*no stress*), >$(0.1\text{–}20)$ % (*low stress*), >$(20\text{–}40)$ % (*moderate stress*), >$(40\text{–}100)$ % (*high stress*).

America, Africa and Northern Europe. Conversely, on less than one third (28 %) of areas (Western US, India, South-East China and a belt from the Mediterranean region to Kazakhstan), the *BECCS* scenario demonstrates lower water stress compared to the *CC* scenario, despite of the irrigation for bioenergy.

Thus, without sustainable water management, irrigation of biomass plantations for the purpose of avoiding excessive climate change (3 °C vs. 1.5 °C) would increase water stress significantly in many regions (and also globally, Figure 5.1). The effect of higher water stress due to irrigated biomass plantations is consistent among the different GCMs and ranges from 64 % in IPSL, over 70 % in GFDL, and 72 % in HadGEM, to 79 % in MIROC (Figure C3.1). These variations are potentially due to the precipitation and temperature differences between the GCMs (Figure C3.12, Figure C3.13).

5.3.4 Drivers of water stress

Higher WSI in *BECCS* compared to *CC* could result from differences in climate, land use, or the irrigation of biomass plantations, as these are the distinctive features in our experimental setup. To determine the attributing cause for the higher WSI in BECCS, we thus ran additional pairs of simulations only varying one of these features while fixing the others (see Methods – Attribution of drivers for water stress differences and Figure 5.4a-d). Globally, irrigated biomass plantations are the major driver for higher water stress in *BECCS* (see their extent in Figure 5.5) due to the additional freshwater withdrawals. In regions which are simulated to experience a higher WSI in *CC*, differences are either due to land use or climate (with similar extent). Regarding the difference in land-use patterns (Figure C3.14), we find a large increase in irrigation on areas of the food producing agriculture (including pastures) in RCP2.6 vs. RCP6.0, which, for example, explains the patterns for the Western United States. The higher water stress in *CC* compared to *BECCS* due to climate differences (mostly in Asia) can be attributed to increases in water availability (see precipitation difference in Figure C3.12).

Comparison of the drivers between GCMs shows relatively high agreement in the Americas and Africa (Figure 5.4e). In Europe and Asia, the inter-model variability is higher (no or only two GCMs agree), potentially due to differences in climate inputs and the subsequent impact on river discharge and water availability.

5.3.5 Potentials of sustainable water management

While these results suggest that irrigation for BECCS will lead to stronger increases in water stress than climate change, both globally and regionally, efforts of EFR protection and advanced on-field water management could potentially moderate the effect of irrigated biomass plantations. The respective simulations (scenario *BECCS+SWM*) indicate a strong reduction of the global area under high water stress to 1,224 (1,167–1,327) Mha. The global population under high water stress is limited to 3.66

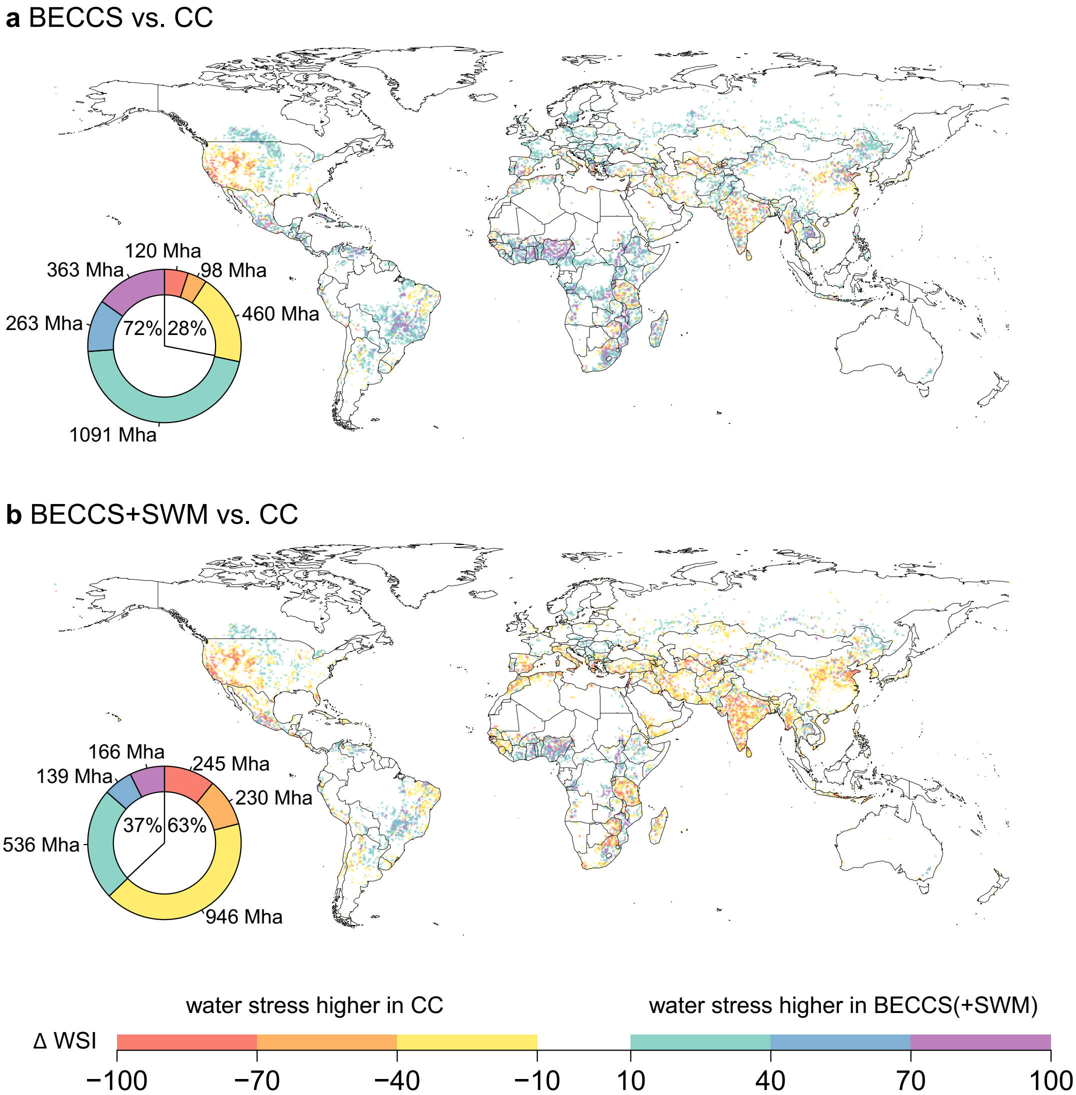


Figure 5.3: Differences in water stress between scenarios BECCS(+SWM) and CC. Shown are differences in mean yearly WSI values (percentage points) among the different scenarios (here, under HadGEM2 climate forcing, 2090-2099 average). Pie diagrams show the total global area showing a certain (respectively coloured) difference.

(3.47–3.85) billion people. Both area and population in *BECCS+SWM* are reduced to below the values derived for the *CC* scenario (Figure 5.1). Also the globally aggregated area under increased water stress would be lower (reduction from 72 % to 37 % – Figure 5.3b), indicating that this scenario globally leads to lesser water stress compared to a scenario with stronger climate change and no bioenergy (maps for all GCMs: Figure C3.2). This demonstrates that irrigation for BECCS, accompanied by policies directed toward more sustainable and effective freshwater use (here, protection of EFRs and improvements in on-farm water use efficiency including on food-producing cropland), could help avoid aggravation of water stress. However, significant challenges including investment potential and water resource management practices may hamper implementation of these policies globally. Moreover, there are regions where even these optimal conditions cannot consistently improve water stress conditions (across GCMs) beyond those of *CC* (Eastern USA, parts of South America, parts of Central and Southern Africa, and parts of Central Europa) (Figure C3.2). Supplementary Figure C3.16 illustrates that, despite SWM, irrigation for BECCS is still the main driver, suggesting that water availability does not allow significant human water withdrawals in these regions.

5.4 Discussion

We conclude that climate mitigation via irrigated BECCS (in an integrated scenario based on RCP2.6), assessed at the global level, will exert similar, or even higher water stress than the mitigated climate change would (in a scenario based on RCP6.0). This confirms (with the exception of the Western United States) results from a previous study for the United States, where irrigated bioenergy plantations were suggested to increase the annual water deficit in comparison to a climate mitigation scenario (Hejazi et al., 2015), albeit the study has different assumptions on land-use and climate trajectories and uses a very different model. Potential hotspots for future water scarcity due to irrigated bioenergy as previously highlighted by the same authors (Hejazi et al., 2014), do not resemble the patterns which we find, suggesting the need for a larger model intercomparison.

Our results also show that globally, the number of people exposed to severe water stress will generally increase due to climate change and expected population growth (Hanasaki et al., 2013b; Gosling and Arnell, 2016). It is thus imperative to minimize additional water demand in an already highly water stressed world, considering also the strong regional differences highlighted in this study.

We thus explicate the dilemma that on top of technological as well as socio-economic barriers to large-scale BECCS deployment (Smith et al., 2016; Fridahl and Lehtveer, 2018; Gough et al., 2018), the production of required amounts of biomass (and thus NEs) is further challenged due to freshwater limitations (imposing higher water stress). The reduction of biomass productivity through only cultivating rainfed biomass plantations and discouraging irrigation (50 GtC over the century – Figure 5.6), however might make the difference between 1.5 °C and (likely) 2.0 °C scenarios (87 GtC)

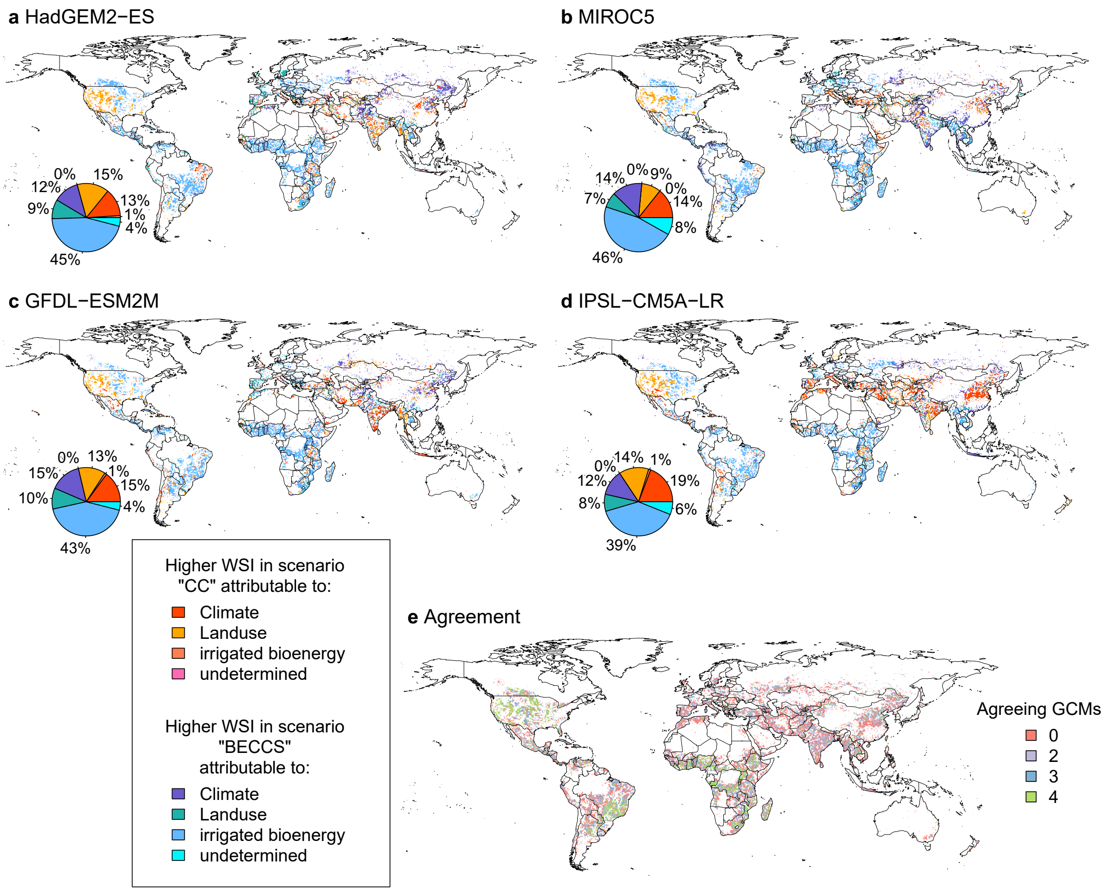


Figure 5.4: Attribution of main driver explaining differences in water stress between the scenarios *BECCS* and *CC*. (a-d) Higher water stress in *BECCS* is indicated by blueish colours, the opposite in reddish colours. Drivers are attributed by factorial simulation experiments keeping either land use, climate or irrigation on biomass plantations constant (see Methods – Attribution of drivers for water stress differences). The global area shares of each category are displayed to the bottom-left of each map. (e) Number of GCMs that agree on the attributed driver in a grid cell.

(Rogelj et al., 2015). This highlights the need to include water availability limitation in integrated assessment scenarios that look at stringent mitigation futures such as a 1.5 °C world, because it may change the balance of which NE technologies may appear in those scenarios.

Finally, we show that implementation of more efficient water management (in scenario *BECCS+SWM*) could offer a synergistic way out of the water stress dilemma. Achieving this requires stringent implementation of such methods worldwide (Smakhtin, 2008; Poff and Matthews, 2013; Jägermeyr et al., 2016), while the required large economic investments (10–20 billion US$ for Africa alone (Rockström and Falkenmark, 2015)) would also help achieving several SDGs (Jägermeyr, 2020).

Growing evidence suggests that next to the direct influence of irrigation on freshwater availability which we account for here, changes in the evapotranspiration regime due to land-use change and especially irrigation may also indirectly influence patterns of local rainfall (Alter et al., 2015; Szilagyi and Franz, 2020), and may have remote effects via atmospheric moisture recycling (Harding and Snyder, 2012b; Pei et al., 2016) or effects on specific and relative humidity (Mishra et al., 2020). Taking these effects into account requires either a coupled biosphere-atmosphere model or a complex redistribution along atmospheric moisture tracks (Tuinenburg and Staal, 2020) for each climate scenario, which open up avenues for potential future research.

Water stress is just one aspect of the wide-range of potential impacts of climate change. Similarly, also every technology designed to avoid climate change will entail (potentially not yet known) side effects, which can even be beneficial in some regions but detrimental elsewhere. In this regard, more holistic analyses of the consequences of mitigation portfolios are required that take into account all dimensions of the complex Earth system.

5.5 Methods

5.5.1 The dynamic global vegetation model LPJmL

All simulations are conducted with the process-based Dynamic Global Vegetation Model LPJmL (Schaphoff et al., 2018a,b). The global land surface is separated into 67420 cells from a 0.5° x 0.5° global grid. Daily terrestrial carbon fluxes for establishment, growth and productivity of natural vegetation and agriculture on managed land (Bondeau et al., 2007) are simulated dynamically based on climatic conditions. Hydrological processes consider blue and green water fluxes, connected by a river routing network including dams and reservoirs (Gerten et al., 2004; Rost et al., 2008; Biemans et al., 2011). Sowing dates for 12 crop functional types plus a group of other annual and perennial crops are dynamically calculated (Waha et al., 2012) and calibrated to match national yield statistics (Fader et al., 2010).

Additionally pastures and two groups of second generation bioenergy crops (woody and herbaceous) are considered. Woody species resemble temperate willows and poplars or tropical *Eucalyptus*, while herbaceous species are parametrised as *Miscanthus* and switchgrass (Beringer et al., 2011; Heck et al., 2016b; Boysen et al., 2017b). Field data were used to evaluate bioenergy yields against (Heck et al., 2016a). A single water use input for SSP2 (to be used in all our scenarios) is prescribed (ISIMIP2b provided multi-model mean domestic and industrial water withdrawal and consumption generated from the ISIMIP2a varsoc runs of WaterGAP, PCR-GLOBWB, and H08 (Wada et al., 2016)). Agricultural areas can be rainfed or irrigated, based on three irrigation techniques: surface, sprinkler and drip (Jägermeyr et al., 2015). To improve water use efficiency, management strategies like mulching, local water storage and conservation tillage can be applied on a grid-cell level (affecting both cropland and bioenergy plantations) Jägermeyr et al. (2016).

LPJmL can also restrict water withdrawals for irrigation to sustain Environmental Flow Requirement (EFRs), which are calculated from the mean monthly discharges of the last undisturbed period of 1670–1699, before human land use is introduced. Based on the VMF method (Pastor et al., 2014), 60 % [45 %, 30 %] of the local discharge in low [intermediate, high] flow months are withhold to secure riverine ecosystems. The flow regime of a given month is defined through comparison with the mean annual flow. Intermediate-flow months are defined by a mean monthly flow of >40 % and <80 % of the mean annual flow, low flow months below, and high-flow months above this range.

Within a grid cell crops are assumed to compete with bioenergy plantations for irrigation water. So by cultivating irrigated bioenergy in water-scarce regions or by restricting withdrawals based on EFRs, crop yields are reduced. Possible solutions for potential yield losses resulting from these strict sustainability scenarios have been previously discussed (Gerten et al., 2020; Heck et al., 2018). In our scenarios with water management, the yield decreases are approximately balanced by more effective water management (see Figure C3.15), which is also applied to cropland (Jägermeyr et al., 2017). In our simulations, irrigation water demand, which cannot be met by local surface water availability (or would tap EFRs) can also be fulfilled by available water in neighbouring cells. Fossil groundwater resources are not considered, but renewable groundwater resources are included as part of the river discharge (baseflow). Return flows are routed back to the river network.

We acknowledge only using a single simulation model. However, the results reported here are largely controlled by the external climate and land-use inputs.

5.5.2 Climate and land-use change scenarios

For maximum consistency, LPJmL was only forced with input from the ISIMIP2b protocol (Frieler et al., 2017). This includes daily climate data from four General Circulation Models – GCMs – (HadGEM2-ES, MIROC5, GFDL-ESM2M, IPSL-CM5A-LR), as well as cell-based projections of water use (Wada et al., 2016) and GCM-specific land-use patterns (including both food and biomass crops) based on the land allocation model MAgPIE (Dietrich et al., 2019) for RCP2.6 and RCP6.0 based on SSP2 (Van Vuuren and Carter, 2014). MAgPIE simulations ensure that the food demand required also by growing population is met, including global trade flows to redistribute products and investment in technological change through which crop productivity can be increased.

LPJmL simulations are performed with an initial spin-up of 5000 years of potential natural vegetation (based on pre-industrial control-climate) to bring global carbon pools to an equilibrium, followed by 307 years of transient spin-up using ISIMIP2b land-use patterns from 1700 to 2006. From 2007 to 2100, land use calculated by MAgPIE follows projections aiming at "fulfillment of food, feed and material demand at minimum costs under socio-economic and biophysical constraints" (Bonsch et al., 2016) (see Figure C3.15 for the development of total crop harvests). It needs to be noted, that downscaling of land-use patterns from MAgPIE regions to the ISIMIP2b grid has not been based on local water availability. For stringent mitigation scenarios, taking into account this potential yield decreasing effect of water limitations on irrigated crop locations might however be desirable.

The climate and land-use trajectories used in this study serve as internally consistent scenarios representing a world with limited climate change through large scale BECCS, which is compared with a strong climate change world. The ISIMIP2b framework is unique for preparing these internally consistent scenarios. Future versions might include more detailed and higher resolution atmospheric as well as land-system processes (e.g. effects of moisture recycling or sea level rise), and potentially even include complex process couplings which could explain global tipping points (Steffen et al., 2018). Resilience to complete deforestation, for example, depends on the region and also on the timing of the forest loss (Staal et al., 2020). Including such processes would eventually also allow for even more detailed water stress analyses.

Our results are valid for comparing water stress in the two given climate scenarios with approximate GMT increases (inter-model mean rounded to the closest half-degree) 1.5 °C and 3 °C in 2100 (Frieler et al., 2017) (RCP2.6 – 1.68 °C and RCP6.0 – 3.15 °C) and should be understood as such. Any deviation from the given trajectories (faster/slower emission reductions than envisioned, the crossing of tipping points, or newly discovered Earth system behaviour) would require the analysis of the corresponding data.

5.5.3 Determining the bioenergy irrigation amount

The ISIMIP2b protocol considers bioenergy plantations for means of energy generation and to realize NEs by BECCS (Figure 5.5). Due to land scarcity and potential productivity increases through irrigation, BECCS is likely going to be irrigated to a substantial degree (Beringer et al., 2011; Stenzel et al., 2019), however in ISIMIP2b irrigation for bioenergy plantations in the land-use scenarios is not included. Instead, the land-use projections are based on increasing productivity on cropland due to technological change (Dietrich et al., 2014), which can be invested in, but does not have any effect on the plant physiology (e.g. higher water demand through development of genetically modified cultivars with higher leaf area index). LPJmL does not include such

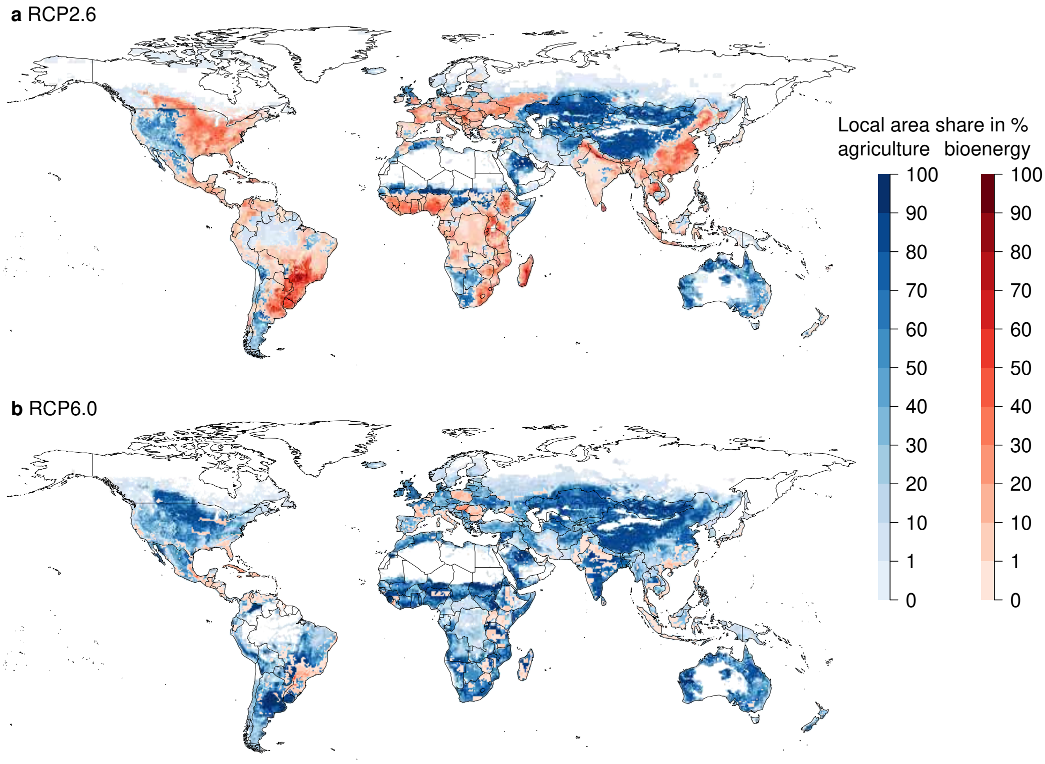


Figure 5.5: Grid cell area shares of food crops and pastures (blue) overlain with those of bioenergy (red) for 2090-2099 in the associated land-use scenarios for RCP2.6 and RCP6.0 (616/29 Mha) in ISIMIP2b for the GCM HadGEM2-ES. Maps are similar for IPSL-CM5A-LR (623/32 Mha), MIROC5 (592/32 Mha) and GFDL-ESM2M (596/28 Mha) (see Figure C3.17, Figure C3.18, Figure C3.19).

technological change and yield increases require additional irrigation or water management efficiency improvements. Therefore the simulated yields on the given land-use patterns are lower than what was initially assumed for ISIMIP2b. We call this scenario *Baseline* (no irrigation of bioenergy plantations).

Since we focus on quantitative effects of irrigated bioenergy plantations as a productivity increasing management option, we estimated the amount of irrigation, which could reproduce the initially assumed bioenergy harvests to stay consistent with SSP2 and RCP2.6, (under the given water policy and management conditions). We thus performed a sensitivity analysis by equipping a fraction of the bioenergy plantation area share per grid cell from 0 % to 60 % in 15 % steps (irrigation level) and then focused on those scenarios in our analysis, which could explain ~50 % of the additional bioenergy productivity increases over the 21st century in the ISIMIP2b demand compared to our baseline scenario with only rainfed bioenergy plants (Figure 5.6). The remaining 50 % were assumed to be met by technology improvements, which do not have a direct effect on the water cycle (e.g. more efficient usage in labour or capital). The irrigation level that matched this criterion best, is 30 % (*BECCS*).

For scenario *BECCS+SWM*, the irrigation level had to be increased to 45 %, due to the withdrawal restrictions for environmental flow protection (for scenario overview see Table S1).

Since the irrigation level was applied globally to all bioenergy grid cells, it also introduced irrigation to cells with low local water availability. Withdrawal restrictions in the *BECCS+SWM* scenario then effectively turn the cells bioenergy plantations to pure rainfed again.

The employed land-use patterns for agriculture and bioenergy as a result of a global optimization would be different if irrigated bioenergy plantations had not been excluded in the ISIMIP2b protocol Bonsch et al. (2016). Reaching the same biomass harvest with irrigation potentially requires less plantation area, which could be substituted with other crops. This motivates continued research in defining sustainable regional specific irrigation thresholds and locations based on our water stress maps and a full integration of EFRs and irrigation related parameters into current integrated assessment models.

The ISIMIP2b protocol already includes agricultural residues as additional biomass source for BECCS or biofuel production (Klein et al., 2014). Recent studies suggest that there might be an additional potential for utilization of organic wastes, which could reduce the raw biomass demand, and thus reduce land or water requirements (Pour et al., 2018).

5.5.4 Water stress index WSI

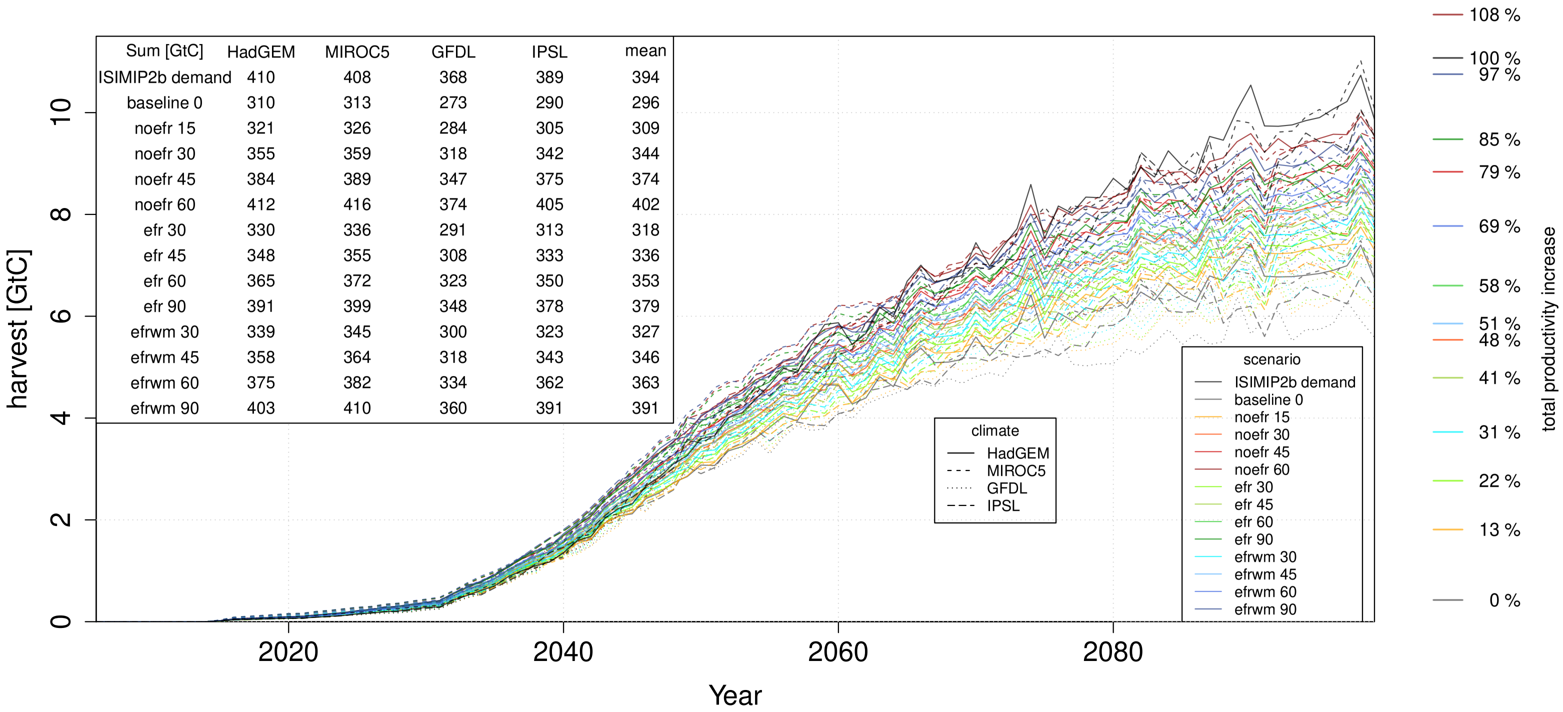
The water stress index (WSI) is computed individually for each grid cell on a monthly basis as a 10 year average percentage of human water use (withdrawals) compared to total river discharge (which includes renewable groundwater) (Raskin et al., 1997).

$$\textit{water stress index} = \frac{\textit{domestic} + \textit{industrial} + \textit{irrigation water use}}{\textit{total discharge}}[\%] \tag{5.1}$$

From the monthly values, we calculate a mean yearly water stress as the main WSI indicator for this study. In the supplementary information, we perform the same analysis also with cell based maximum water stress (Figure C3.20, Figure C3.3, Figure C3.5, Figure C3.7, Figure C3.9), as the water stress of the mostly stressed month (see Figure C3.21 for a map of these months in scenario *BECCS*).

5.5.5 Attribution of drivers for water stress differences

The differential water stress maps (Figure 5.3) show in which of the two compared scenarios (*BECCS* or *CC*) the stress is higher, but they do not explain what the driver for this is. Generally it could be due to the differences in climate input, land-use patterns, or the amount of bioenergy irrigation. To perform the attribution, we analyse six scenarios, where pairs of them only differ in one regard (climate input, land-use patterns, or irrigated bioenergy extent). We compare the WSI in these three pairs (CCdiff, LUdiff, and IBdiff). CCdiff is composed of two simulations with climate from RCP6.0 and



Sum [GtC]	HadGEM	MIROC5	GFDL	IPSL	mean
ISIMIP2b demand	410	408	368	389	394
baseline 0	310	313	273	290	296
noefr 15	321	326	284	305	309
noefr 30	355	359	318	342	344
noefr 45	384	389	347	375	374
noefr 60	412	416	374	405	402
efr 30	330	336	291	313	318
efr 45	348	355	308	333	336
efr 60	365	372	323	350	353
efr 90	391	399	348	378	379
efrwm 30	339	345	300	323	327
efrwm 45	358	364	318	343	346
efrwm 60	375	382	334	362	363
efrwm 90	403	410	360	391	391

Figure 5.6: Global bioenergy harvest per year for scenarios with $0, 15, 30, 45, 60$ or $90\,\%$ irrigation and no EFR protection (noefr), as well as EFR protection (efr), and EFR protection plus water management (efrwm) for the GCMs HadGEM2-ES, MIROC5, GFDL-ESM2M and IPSL-CM5A-LR. The ISIMIP2b biomass demand is calculated from the LPJmL yield of the *Baseline* scenario multiplied with the initially assumed productivity increases from MAgPIE. Additionally displayed is the total bioenergy harvest sum over the 21st century of each scenario together with the inter-model mean, which for each scenario is shown on a scale of total productivity increases by technological change from $0\,\%$ (*Baseline*) to $100\,\%$ (ISIMIP2b demand). For further analysis we select scenarios, which can explain $\sim 50\,\%$ of the productivity increase by the scenario specific parameters.

RCP2.6, but the same RCP2.6 land use without irrigated bioenergy to analyse the climate change contribution. LUdiff is based on two simulations with land use from RCP6.0 and RCP2.6 without irrigated bioenergy, but the same climate from RCP2.6 for the land-use contribution. IBdiff is calculated from two simulations with irrigated and non-irrigated bioenergy land use from RCP2.6 and the same climate from RCP2.6 to quantify the irrigated bioenergy component. If a grid cell shows higher water stress in the *BECCS* scenario, and the absolute of IBdiff is more than 20 % higher than that of CCdiff and LUdiff, we mark the cell as *Higher WS in scenario BECCS attributable to: irrigated bioenergy* (and similar for the other 2 cases). Should 2 or 3 drivers apply at the same time (the differential stresses CCdiff, LUdiff and IBdiff are similar), we mark the cell as *undetermined*.

5.6 Acknowledgement

This study was funded by the CE-Land+ project of the German Research Foundation's priority program SPP 1689 "Climate Engineering – Risks, Challenges and Opportunities?". Part of the research was developed in the Young Scientists Summer Program at the International Institute for Applied Systems Analysis, Laxenburg (Austria) with financial support from the German National Member Organization (Association for the Advancement of IIASA). PG and YW are financially supported by EUCP (European Climate Prediction System) project funded by the European Union under Horizon 2020 (Grant Agreement: 776613). We thank Miodrag Stevanović for providing the technological change factors underlying the land-use scenarios applied. All figures were created using R (R Core Team, 2020), maps are based on the R package "maps" (Becker et al., 2018).

6 Synthesis

This chapter provides answers to the research questions (section 6.1) and a discussion of the results. I put into context the potentially large water demand for bioenergy with projections for other water uses, discuss pathways to achieve 1.5 °C with irrigated bioenergy and analyse the water stress resulting from large scale irrigated bioenergy plantations in several future scenarios (section 6.2.1).

Furthermore, I discuss aspects that go beyond the results from the three published studies and look at methodological obstacles (section 6.2.2), barriers and alternative solutions to large scale BECCS deployment (section 6.2.3, section 6.2.4), legal and ethical arguments regarding climate engineering approaches in general (section 6.2.5), additional opportunities and a reality check of water management (section 6.2.6, section 6.2.7), drivers and remote effects of large scale irrigation (section 6.2.8, section 6.2.9), and trade-offs between Planetary boundaries and food security (section 6.2.10). Within the discussion, I also highlight potential avenues for future research. In section 6.3 I summarize my key learnings.

6.1 Answers to the research questions

P1 - Which key modelling assumptions control the projected global freshwater demand for irrigation of bioenergy plantations?

Projections of future irrigation water requirements for biomass plantations are derived with a variety of methodologies and models. They can be grouped into supply and demand driven studies, with two main approaches:

1. Extrapolation of current evapotranspiration from bioenergy field studies for future energy demand scenarios
2. Process model assessments controlled by future scenarios of e.g. socio-economic or land-use development

Reported values on the global water demand for irrigation of biomass plantations suggest water withdrawal in the (large) range of 128.4–9,000 $km^3\ yr^{-1}$, which would come on top of (or compete with) 1,100–11,600 $km^3\ yr^{-1}$ for other (agricultural, industrial, and domestic) water withdrawals. Total plantation area and locations, global biomass harvest, and carbon conversion efficiency are identified as key parameters. The spread in the additionally calculated inverse water use efficiency (water requirements per biomass harvest), however, shows that the freshwater demand is not only controlled by these parameters alone, but also the remaining differences and assumptions. One main conclusion is that full disclosure of parameters and assumptions is crucial to interpreting and comparing reported estimates of possible future bioenergy water demands. Additionally, the water demands for bioenergy and the trade-offs that might go along with them should be an integral part of future global assessments of freshwater demand and use. The publication is supported by a synthesis database which lists parameters and assumptions for the analysed studies and will inform and assist in parameter choice for future studies.

P2 - What is the potential of optimal bioenergy plantation locations and sustainable water management for achieving the 1.5 °C target?

Our simulations are based on a stylized future scenario, which comprises a cumulative NE demand of 255 GtC in order to limit GMT rise to 1.5 °C. The associated irrigation water demand is assessed for optimally located bioenergy plantations (maximum water efficiency) in four water management scenarios (RF, IRR, EFR, WM) under a baseline parameter set and two development pathways (TechUp, IrrExp).

This systematic exploration of the parameter space yields that the required NE demand is very difficult to reach except under the most ambitious assumptions (highly efficient BECCS systems exceeding 50 % carbon conversion efficiency or strong irrigation expansion without withdrawal limitations).

Consideration of EFRs reduces the NE potential significantly but can partly be compensated for by improved on-field water management.

The results for total amount of additionally required bioenergy irrigation water can be grouped in three different classes of parameter assumptions (Figure B2.3):

- high (1,368–2,239 $km^3\,yr^{-1}$) for scenarios with no upper limit to the irrigation area
- medium (587–642 $km^3\,yr^{-1}$) for scenarios without EFR restrictions, but limited irrigation area
- moderate (361–383 $km^3\,yr^{-1}$) for scenarios with EFR protection and limited irrigation area

This suggests that either irrigation intensification or highly efficient BECCS systems exceeding 50 % carbon conversion efficiency will be needed (or a combination of both).

P3 - Do irrigated bioenergy plantations have a larger effect on water stress than the avoided climate change?

Irrigation for BECCS might introduce large additional water demands (especially to reach ambitious climate targets like the Paris Agreement). On the other hand, higher global mean temperatures as a result of failed mitigation (without large-scale BECCS) are likely to increase water stress, too. Area and population exposed to high water stress are simulated to almost double (88–101 % increase) in 2095 in a 1.5 °C scenario with irrigated BECCS compared to today. This increase is higher than a scenario with unmitigated climate change (CC) in a 3 °C world (54–82 % increase).

Complementing the global assessment, the drivers for water stress (climate, land use, bioenergy irrigation) were also compared on a grid cell level between scenarios BECCS and CC. The additional freshwater withdrawals for irrigated biomass plantations are the major driver for higher water stress in BECCS. However, there are also regions which are simulated to experience higher water stress in CC. This is mostly due to land-use changes on areas of the food producing agriculture, or decreases in water availability due to the higher temperature (to similar extent).

Sustainable water management as a combination of withdrawal restrictions via EF protection and increased on-farm water use efficiency might enable to reduce the pressure on freshwater resources and should therefore be an integral part of a NE strategy based on BECCS.

6.2 Discussion

6.2.1 General discussion of research results

BECCS is considered an important part of ambitious climate change mitigation scenarios. However, in order to provide the required negative emissions to limit GMT increase to below 2 °C, it is likely to substantially increase global irrigation water use if not properly governed. Global freshwater withdrawals might double during this century, which could also double the number of people living under high water stress. Dramatic socio-political consequences could be the result of this given that long-term water stress can lead to the destabilization of whole regions (King, 2015) and intra-basin conflicts over water use allocations (e.g. dam construction Wheeler et al. 2020) are on the rise.

On the global scale, I have shown that humanity is facing a dilemma, where water stress is going to increase regardless of whether climate change or large scale BECCS for climate change mitigation is going to become reality. The range and uncertainty in the projections for future water use of all sectors is huge, with many scenarios significantly transgressing the planetary boundary for freshwater use (Figure 6.1). The only way out of the dilemma would be the implementation of sustainable water management with stringent withdrawal policies and water use efficiency improvements worldwide, a very challenging task.

My results further highlight the need to better understand the socio-economic framework and drivers that might influence the irrigation on biomass plantations together with the urgent need for policies to prevent large scale additional water stress. This policy framework should already be discussed now, as the implementation of biomass plantations is already an important component of socio-economic scenarios which influence long-term political decisions. Furthermore, a lot of research is yet to be done to better understand the complex interplay between humans and the Earth system, influenced by climate engineering through biomass plantations.

Subsequently, I will discuss further aspects beyond the content of the published papers, which might be worthwhile to analyse in upcoming research projects.

6.2.2 Methodological obstacles

The LPJmL model relies on several inputs, the most relevant for this thesis being climate, land-use, and water use. One challenge is to use a set of products that is consistent, which even for the historic period is not always given. Climate input is for example often bias corrected, because of the differences between GCMs. This means that the GCM specific outputs are corrected based on comparison of how the model performs in a reference period of observed data (Hempel et al., 2013). This has the advantage that all models are approximately comparable at this time, but the side-effect that they diverge before and afterwards. However, the re-analysed historic climate data might not be fully

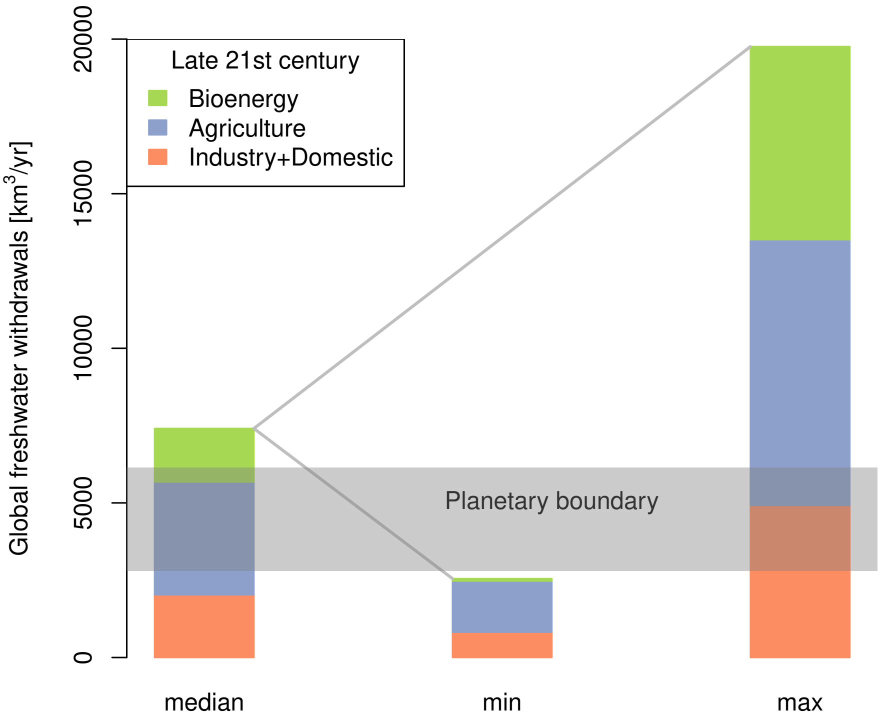


Figure 6.1: Projections for late 21st century water withdrawals with median, minimum and maximum of each category (irrigation for bioenergy, irrigation for food producing agriculture, Industry/Domestic water use) based on the literature review conducted in chapter 3. The range 2,800–6,410 $\mathrm{km^3\,yr^{-1}}$ for the planetary boundary for freshwater is based on Gerten et al. (2013a) and Brauns (2016).

consistent any more with the datasets used for the GCM runs, e.g. land-use patterns. Future land-use datasets often undergo a harmonization process, which removes a potential offset between the end of historical reconstructions and initial conditions in IAMs, while the future projections are supposed to be preserved (Hurtt et al., 2020). During this, land-use types are sometimes shifted. In the case of the harmonization during ISIMIP2b for example (LUH), some of the biomass plantations that were only assumed as rainfed were turned into irrigated (Hurtt et al., 2011).

More complex setups and modelling chains can lead to further discrepancies. While writing this thesis, it was discovered that the initial assumptions for biomass demand for ISIMIP2b from the energy-economy model REMIND are over-fulfilled, when the final land-use patterns are run again in LPJmL. Reasons for these differences are not fully understood. Major factors are likely the harmonization and that all models have been updated since the start of ISIMIP2b.

In summary, a stronger integration of the water availability and demand seems vital to future scenario assessments. Additionally (also as a conclusion from chapter 3), a multi-scenario model inter-comparison for location specific BECCS water demands seems to be the next logical step. The integration of portfolios of NETs (more diverse, each deployed at smaller scale) with potential co-benefits is likely to also change the strong dependence on BECCS (Fajardy et al., 2019; Köberle, 2019).

6.2.3 Implementation obstacles to BECCS

The analysis of side-effects of the implementation of BECCS in this thesis focused on the physical world and potential freshwater demands. Food security and biodiversity loss are further sustainability issues of large-scale BECCS deployment (Smith et al., 2016), together with the unknown presence of safe, long-term geologic carbon storage capacity (Gough et al., 2018; Vaughan et al., 2018). Additionally, the unknown responses of natural land and ocean carbon sinks to negative emissions are highlighted (Fuss et al., 2014). These responses might oppose large scale carbon dioxide removal, and release additional carbon as a result of the changed trends in the atmosphere. Another challenge includes the costs and financing of an untested CCS technology, which might slow down its global uptake (Reiner, 2016). Lastly, socio-institutional barriers are identified as challenging, which are related to public acceptance of this new technology and its deployment. This lack of socio-political acceptance could potentially be one reason for the gap between perceived domestic and global potential (Fridahl and Lehtveer, 2018). Like other large transformations, BECCS might be influenced by a "not-in-my-backyard" mentality.

6.2.4 Alternative solutions to BECCS

Instead of "betting on" possible future NEs (Fuss et al., 2014), the safest way to avoid the most severe climate change impacts is to reduce emissions as soon and as strongly as possible. This means to quickly and radically increase the share of renewable power sources. Additionally, land-use patterns could be optimized towards local self-sustainability, transport emissions of agricultural goods could be reduced (Kriewald et al., 2019; Pradhan et al., 2020), or management on cropland and pastures improved to reduce agricultural emissions (Smith et al., 2013; Wollenberg et al., 2016).

Further, other NE technologies with fewer side effects are being discussed, among them the application of biochar (charcoal made from biomass via pyrolysis) to soils (PyCCS), which (through increased water and nutrient holding capacity of the soils) would increase crop productivity (Schmidt et al., 2019). There are also potential synergies of PyCCS and BECCS, which could overall reduce environmental impacts including water stress: increased biomass yields (less land or irrigation needed), early use of biomass when geological storages are not yet feasible, and CCS of further pyrolysis products (bio-oil and syngas) in geological storages later on (Werner et al., 2018).

6.2.5 Legal and ethical points to climate engineering

There is a set of moral-ethical arguments about CE, some of which are also applicable to tCDR, like BECCS. From an ethical point of view, mainly three lines of argumentation speak against climate engineering. Those are the "hubris", "moral hazard" and "slippery slope" arguments. The hubris argument is based on previous developments, where humans have overrated their understanding of systemic processes, neglected parts of the available knowledge or wrongly estimated future costs or side-effects of their actions. Along these lines, large scale climate engineering should not be considered an option, because we will have missed some important part of the Earth System and might trigger unwanted consequences (Owen, 2014). The second argument is that of moral hazard, which delineates that counting on having the option of climate engineering will lower counteractions - for example lead to fewer emission reductions - and thus either lead to more CE being required, or making it even harder to reach the goals if CE fails (Hubert, 2020). The slippery slope argument constitutes that researching CE technologies also makes their deployment more likely. This line of argument has been contested, but researchers highlight the need for regulation and oversight in order to prevent undesirable deployment (Callies, 2019). All three arguments are strongly linked with inter-generational justice, because both inaction and action without being fully aware of the consequences might strongly impact the lives of future generations.

Even though the previous points speak against deployment (and the slippery slope argument also research) of climate engineering technologies, there are also arguments for early preparation. Research now might "arm future generations" for deployment should it be absolutely necessary (Hubert, 2020). For SRM, this means that in a case of "climate emergency", a short term use might be considered in order to buy time for CDR (Neuber and Ott, 2020). Markusson et al. (2014) argue, that this argument is flawed as it contradicts the hubris and moral hazard argument, but is rhetorically very hard to defuse. Climate engineering could also be the "lesser evil" compared to climate change impacts. Research and tests might therefore be allowed, should emission reductions fail, but only under "conditionality". This means that states should only be allowed to perform CE research, if certain climate policy conditions are met (climate policy integrity and credibility) and if they engage in climate funds (Stelzer, 2017).

All these arguments are interwoven and the terms used subject to debate. In light of many climate tipping points not being quantified very well and uncertainties and side-effects of climate engineering technologies still largely unclear, Ott and Neuber (2020) doom highly general arguments across all technologies to fall short. So far, ethical arguments based on potentially induced water stress are missing, but my work suggests that these ultimately also need to be considered.

6.2.6 Water management opportunities

My work puts sustainable water management in focus, which consists of EF protection and advanced on-field water management. Additional co-benefits of increased water management lie in the potential reduction of soil erosion, which for example currently affects 67 % of cropland in Sub-Saharan Africa (SSA) (Liniger et al., 2011). At the same time, however, many cropping systems in SSA are chronically nutrient-deficient, so that water management could not be fully effective, unless depleted soils were restored (Sánchez, 2010; Fox and Rockström, 2003). Furthermore, large scale mulching with plastic can lead to environmental pollution (Liu et al., 2014). Biomass plantations could help providing additional organic material to avoid the usage of plastic.

6.2.7 How realistic is global sustainable water management?

The large water saving potentials of sustainable water management as a combination of withdrawal restrictions through environmental flow provisioning and increased on-farm water management highlight the importance of the nine-point global action agenda from the Brisbane Declaration (Brisbane Declaration, 2007). However, it also raises the question of how realistic it is, that these approaches are quickly picked up globally. Hirji and Davis (2009) highlight 17 case studies for environmental flow provisioning from all over the world. Most of them are policy examples (like the European Union Water Framework Directive) or infrastructure cases funded by the World Bank (e.g. in connection to dam construction). These examples show that EF provisioning is gaining momentum, but a global implementation seems very far down the road. Australia's National Water Initiative, for example, seems to take a pivotal role in large scale EF provisioning, according to the authors - owing to "widespread concern about environmental degradation and overallocation of water resources recognized in the 1990s" (p.18). This public awareness might however be missing in other parts of the world.

Environmental flow protection can in theory be achieved physically by water allocation or economically through water pricing. While the first approach raises questions about the feasibility of the rationing, the response in demand to volumetric water pricing has been shown to be minimal (Cornish et al., 2004). Water prices would need to be 20 percent of net income or higher to begin to have significant impact on water use, which would be politically and socially very difficult to implement. Lack of political will and public support are also identified as obstacles to the implementation of environmental flow protection, together with constraints on resources, knowledge and capacity, institutional barriers and conflicts of interest (Arthington et al., 2018).

This shows that global modeling approaches are only the first step towards sustainable trans-boundary water management, and need to be accompanied by socio-political efforts also outside the scientific community.

6.2.8 Drivers for irrigation expansion

There is little research on the drivers for bioenergy irrigation, but even for conventional agriculture the literature is sparse. Neumann et al. (2011) analysed which variables could best explain recent patterns of a dataset for area equipped for irrigation (AEI) by Siebert and Döll (2010). This missing time-dimension is currently under investigation in two master theses in our institute (Rachel Ledig and Sophie Wagner), which also explore historic drivers of irrigation expansion based on the same AEI dataset with a similar approach. The projects employ Bayesian statistical modelling to find out which of a set of potentially influencing variables (e.g. potential yield increase through irrigation, GDP, distance to nearest irrigated plot, ...) best explain the historic trend and what is the difference, as compared to the earlier approach. The results might also provide insights into the potential future expansion of irrigation on bioenergy plantations.

Additionally, a large component of the Earth system is how humans influence each other. However, this information combined with the coupled interactions with the biosphere, only enters statistical models in a parametrized form. Another potential avenue for research in this field is thus socio-hydrological modelling of the involved actors as agents in a coupled human-natural model with their decisions based for example only on the actor specific knowledge and environment, as similarly for example done for land-use in the Amazon by Müller-Hansen et al. (2017). The copan:core framework (Donges et al., 2020) provides a basis for these types of models and the coupling to LPJmL would also possible.

6.2.9 Remote effects of bioenergy plantations

Large scale biomass plantations will have remote effects in the Earth system. Apart from surface albedo changes from replacing vegetation in a different colour (Boysen et al., 2016), they might modify evapotranspiration patterns and hence potentially entail downstream and downwind effects, especially if they are irrigated (Harding and Snyder, 2012a,b). These effects can be detrimental or beneficial and should thus be analysed and considered before the planning phase of the plantations.

Generally, irrigation is found to modify surface energy and water budgets, leading to a modification of the large-scale atmospheric circulation (Pei et al., 2016), but only modestly intensifying the continental water balance (Vervoort et al., 2009). If the irrigated area is large enough, local precipitation is reduced (Szilagyi and Franz, 2020) and in turn enhanced downwind (Alter et al., 2015). This can be explained by latent heat from the cooler, wetter plantations increasing low-level instability and triggering storms (Moore and Rojstaczer, 2002). These effects were confirmed only for some areas of the world (Central US and Egypt) and are strongly dependent on the local settings, weather regimes, topography, other land-uses and more and can only partially be transferred to bioenergy plantations.

This uncertainty promotes computer simulations, however, the analysis of these effects requires a complex Earth System Model. Such models are computationally very challenging, because they need to couple a GCM with a detailed process and high resolution land-use model. Within the POEM framework developed at PIK (Drüke et al., 2021), there might now be opportunities to study these highly relevant effects to, for example, find areas with high water availability, which can support irrigated bioenergy plantations, but at the same time increase downwind precipitation and thus have a positive side effect for these regions. Such controversial intentional large scale weather modifications will add more meaning to the term "climate engineering".

Irrigation for bioenergy fed by surface water also directly reduces the down-stream water availability, as do other water users such as withdrawals for irrigation in agriculture, industry, households, or livestock production. For regions with low water availability, concurring water withdrawals can lead to overuse, if not properly governed. One example of such a problematic socio-hydrological system is the Murrumbidgee River Basin in Australia, where irrigation demands that were higher than water availability led to irrigated plots moving up the river during the 20th century (Sivapalan et al., 2012). The government tried to stop this race of being "the first to withdraw" by drastically increasing water prices and buying back previously irrigated land in the upper river basin. This measure led to a decrease in overall irrigation and moved irrigated plots back downstream. The phenomenon, called the "Murrumbidgee River Pendulum Swing", was also studied with numerical models, which could reproduce it through the interplay between five state variables, governing their co-evolution: reservoir storage, irrigated area, human population, ecosystem health, and environmental awareness (Van Emmerik et al., 2014). This study was among the first in the new field of "Socio-Hydrology" and highlights the need to integrate the co-evolution of human-natural systems also into the research for irrigation of biomass plantations.

As opposed to irrigation withdrawals, EF provisioning increases down-stream water availability. Both effects have region dependent implications for down-stream water use of all sectors (Jans et al., 2018). Combining these contradictory effects could be a next step in how water use models might advance in the coming years.

6.2.10 Planetary boundary trade-offs with food security

Land-based mitigation measures to restore the planetary boundary of climate change might lead to competition for arable land with the food producing agriculture. This threatens food prices to go up, with the consequence that food availability might decrease, putting more than 200 million people at the risk of hunger (Doelman et al., 2019). Here, second generation bioenergy might show no improvements over the first generation, which is attributed to have aggravated the global food price crisis in 2007/2008 (Mitchell, 2008). Therefore, locations for biofuel production are more strictly analysed today (Timilsina and Shrestha, 2010). However, indirect deforestation could still result in net carbon losses (Lapola et al., 2010).

Additionally, the competing water use with the food producing agriculture highlights the need to look at trade-offs between climate change mitigation and other SDGs, such as food security. This might dissuade water scarce regions from large scale implementation (De Fraiture et al., 2008).

On the other hand, the protection of riverine ecosystems in line with staying below the planetary boundary for freshwater use can also lead to food security issues because irrigated crops might receive less water. Strict EF protection would reduce the global kcal production by 4.6 % as presented by Jägermeyr et al. (2017). The authors further show that adjusting irrigation setups and implementing integrated water management worldwide would overcompensate these losses, however, this study did only look at present day and thus neglects effects of climate change, or climate change mitigation, which might exert further pressure on the food system.

While balancing these additional losses, dietary changes might also help to feed a growing population (Gerten et al., 2020), or free up space for significant biomass production and thus negative emissions. A strictly vegan diet would increase the global food supply by 19 %. Reducing the animal protein share to 25 % of the total protein supply would still result in an increase of the global food supply by 4 % (Braun et al., 2021). However, losses and compensations would not be equally distributed globally. In regions with water scarcity (today especially Middle East, South and Central Asia), EFR protection would result in higher yield losses than the global average, whereas North America and Europe would profit stronger than other regions from the dietary change scenarios because crop feed shares there are relatively high and dietary change would allow for more crops to be directly used for food.

This underpins the need for cooperation not only between states of the same river basin to ensure a fair distribution of the available water, but also globally to compensate for potential yield losses resulting from fewer irrigation water supply.

6.3 Policy implications

This work highlights that humanity will be facing huge challenges to mitigate climate change. My studies and also previous assessments yield that besides the potentially large amount of negative emissions BECCS might provide, there are other dimensions of the Earth system that need to be considered to prevent unwanted deterioration of our environment and to minimize impacts for humanity. I focused on the dimension of water, but also e.g. biodiversity loss as a result of large scale land transformations is a severe issue. Thus, mitigation decisions should be based on systemically analysing all social and environmental dimensions of the Earth system. To provide a most valuable and accurate decision base for policy makers, future modelling studies need to incorporate these aspects. The concept of Planetary Boundaries might help in this regard. Further, on a local scale humanity should strive to fulfil all sustainable development goals set by the United Nations, including the right to sufficient amounts of clean water for everyone.

The challenge of climate change is not going to become easier, it is likely that negative emissions might be needed. However, we show that BECCS alone (as the basis of many current scenarios to limit global mean temperature increase to 1.5 °C) might not be the best path forward due to the associated side effects, especially the freshwater demand. Without proper governance, it would leave us stuck in a situation with severely increased water stress, regardless of the climate trajectory. To get out of this dilemma, soon and drastic emission reductions need to be absolutely prioritized, reducing the dependence on negative emissions. For the remaining negative emissions needed, portfolios of technologies need to be intensively studied and consistently modelled because there might be potential co-benefits that help overcome some of the side effects.

A
Supplementary Information to P1

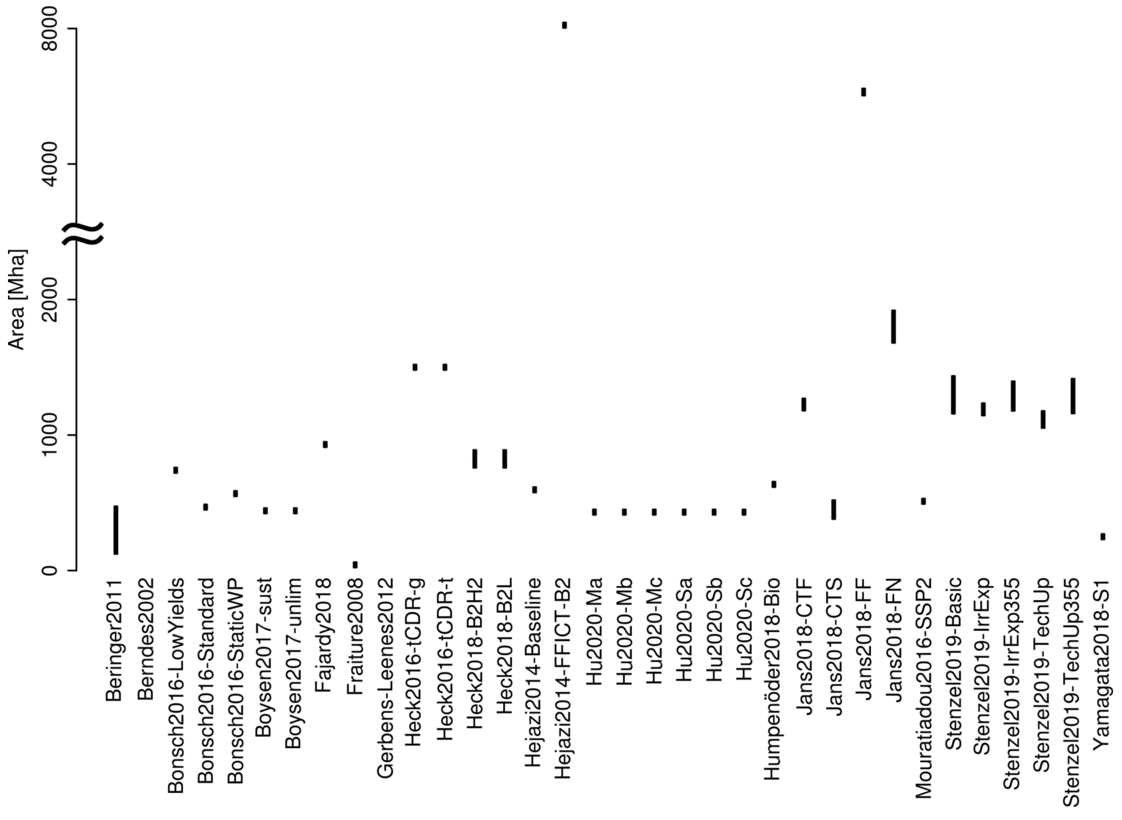


Figure A1.1: Overview of reported total global area of bioenergy plantations.

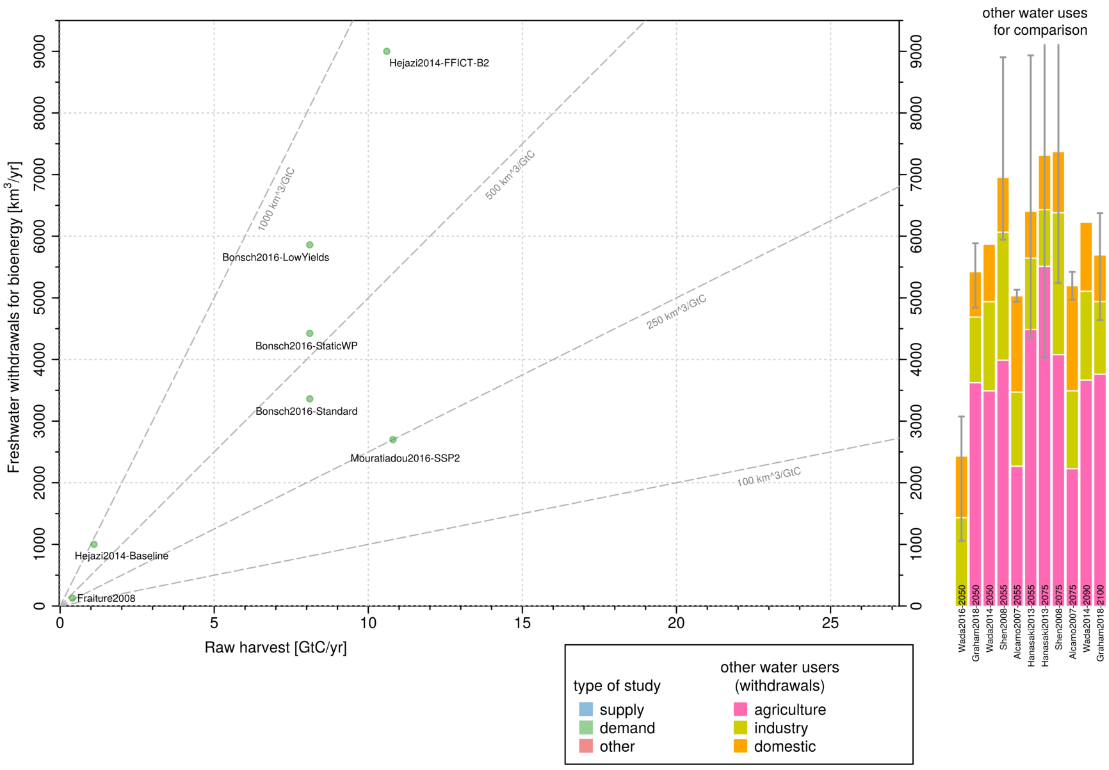


Figure A1.2: Analogous to Figure 3.2 but for scenarios of reported values of global blue water withdrawals required for bioenergy production through biomass plantations. Scenarios are characterized by water withdrawals for bioenergy plotted against raw harvest (inferred from reported biomass based energy or negative emissions). They can provide ranges in water withdrawals or raw harvest (illustrated by boxes), or contain single values (depicted by circles). The type of study is marked by the color.
For contextualization, projections for other water uses (withdrawals) are shown to the right, together with their uncertainty ranges. Names of the bioenergy scenarios are constructed as {author}{publication year}-{scenario name}, those of ”other water use” scenarios as {author}{publication year}-{simulation year}.

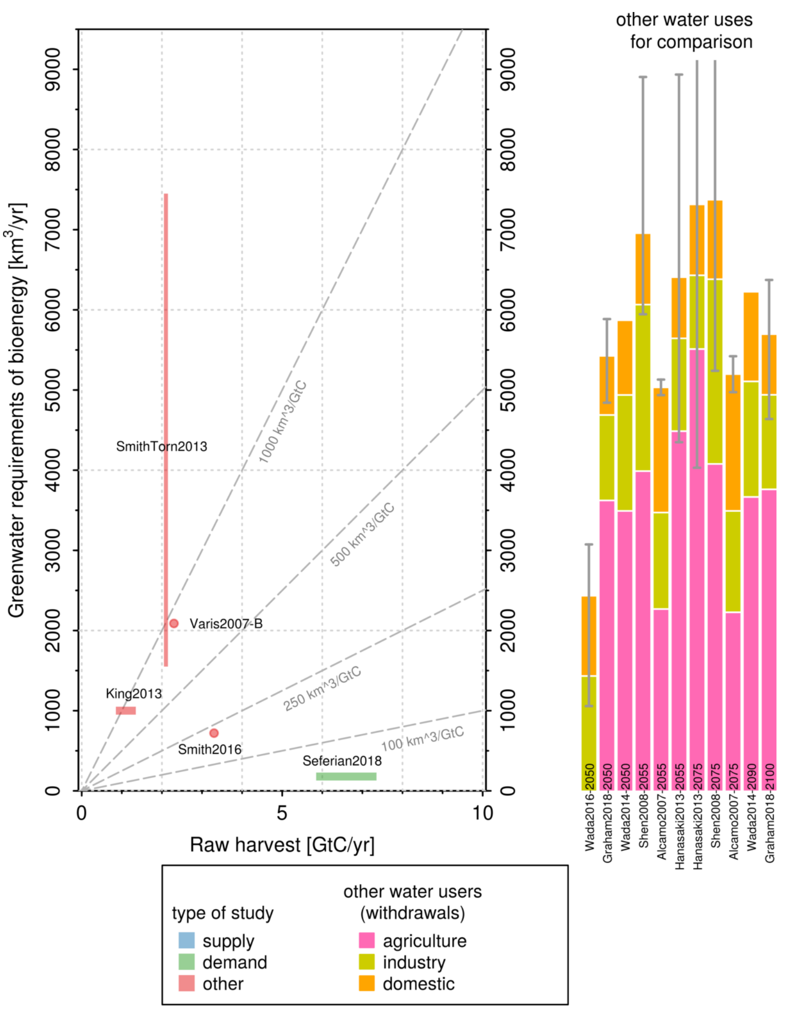


Figure A1.3: Analogous to Figure 3.2, but for scenarios of reported global green water consumption volumes required for bioenergy production through biomass plantations. Scenarios are characterized by water consumption for bioenergy plotted against raw harvest (inferred from reported biomass based energy or negative emissions). They can provide ranges in water consumption or raw harvest (illustrated by boxes), or contain single values (depicted by circles). For contextualization, projections for other water uses (withdrawals) are shown to the right, together with their uncertainty ranges. Names of the bioenergy scenarios are constructed as {author}{publication year}-{scenario name}, those of "other water use" scenarios as {author}{publication year}-{simulation year}.

B

Supplementary Information to P2

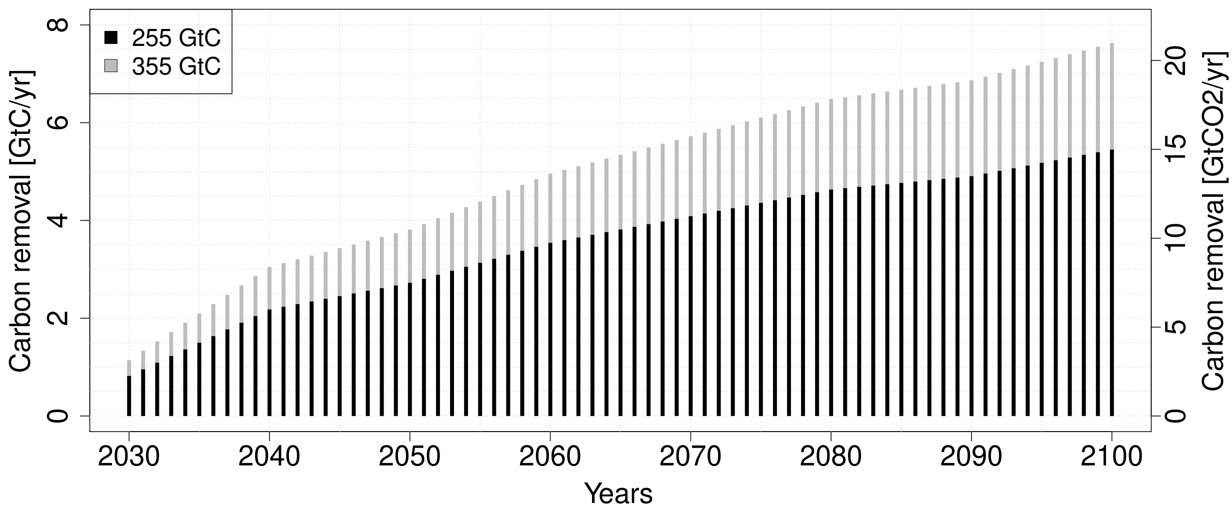


Figure B2.1: Amount of sequestration needed per year to stay within 1.5 °C warming (255 Gt C – black bars), after Rogelj et al. (2015), and to reach a higher sequestration demand of 355 Gt C (grey bars), obtained by linear up-scaling of the 255 Gt C curve.

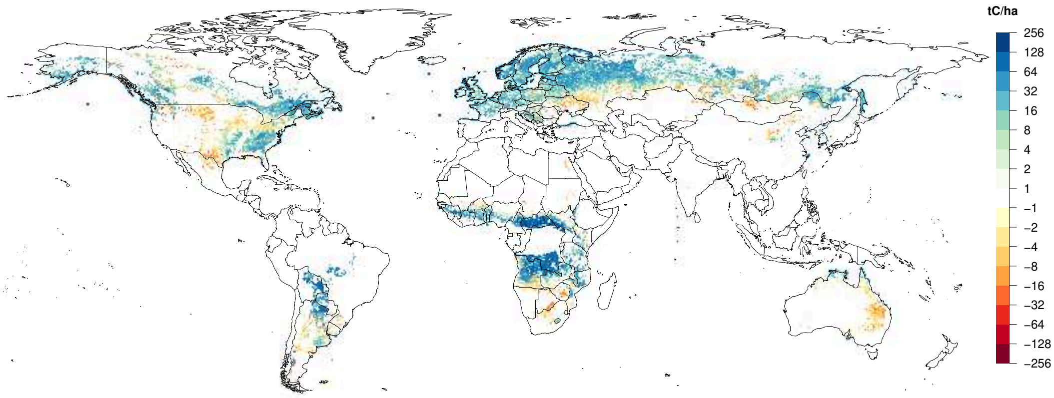
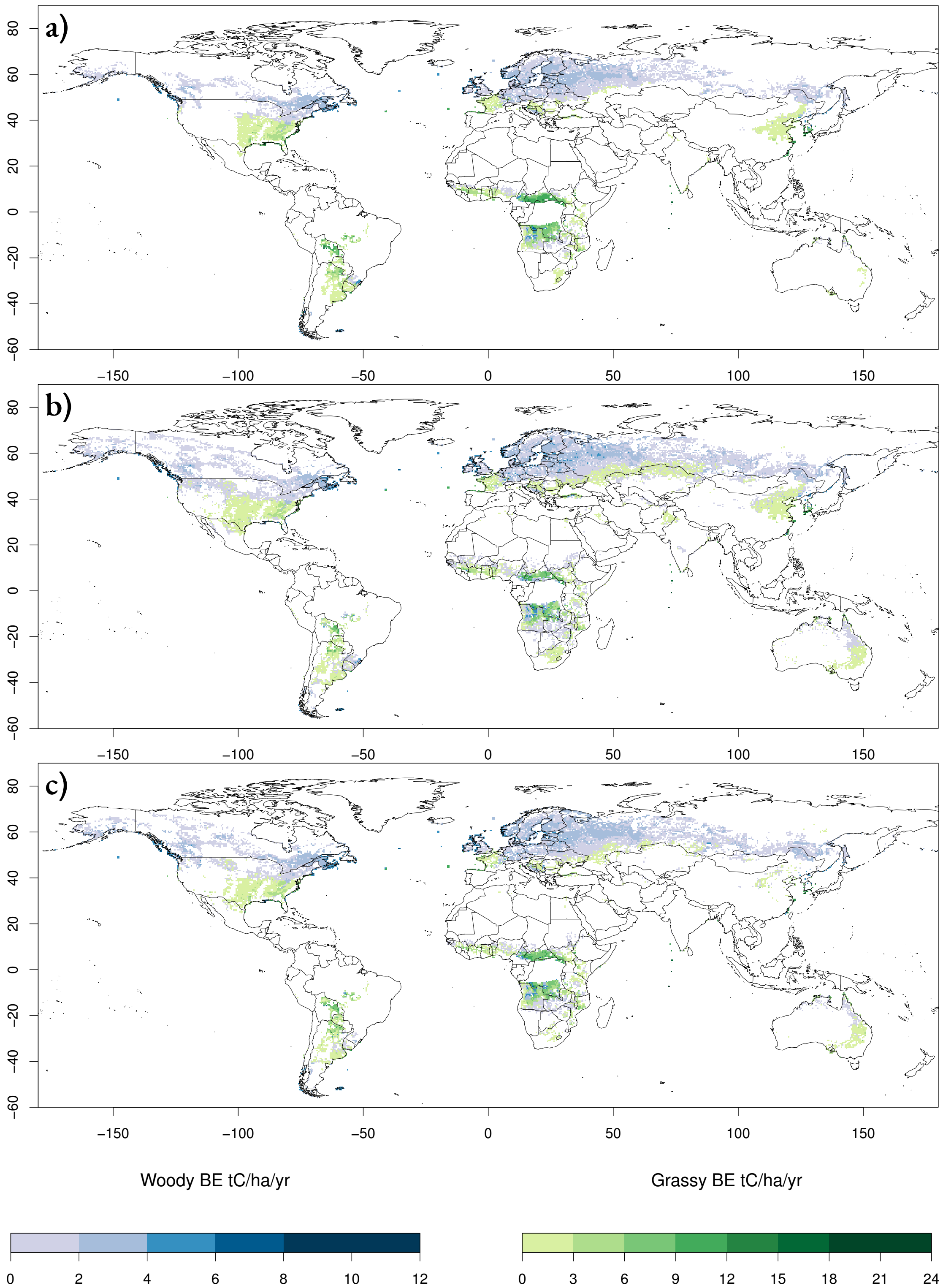


Figure B2.2: LPJmL-simulated LUC emissions for scenario WM and Basic parameter set, computed as the difference (2090–2099 average) relative to the reference run without BPs of the sum of the mean carbon content in soil, vegetation and litter pools, shown exemplarily for the TechUp parameter set and scenario WM.


a)
b)
c)
80
60
40
20
0
−20
−40
−60
−150
−100
−50
0
50
100
150
Woody BE tC/ha/yr
0 2 4 6 8 10 12
Grassy BE tC/ha/yr
0 3 6 9 12 15 18 21 24

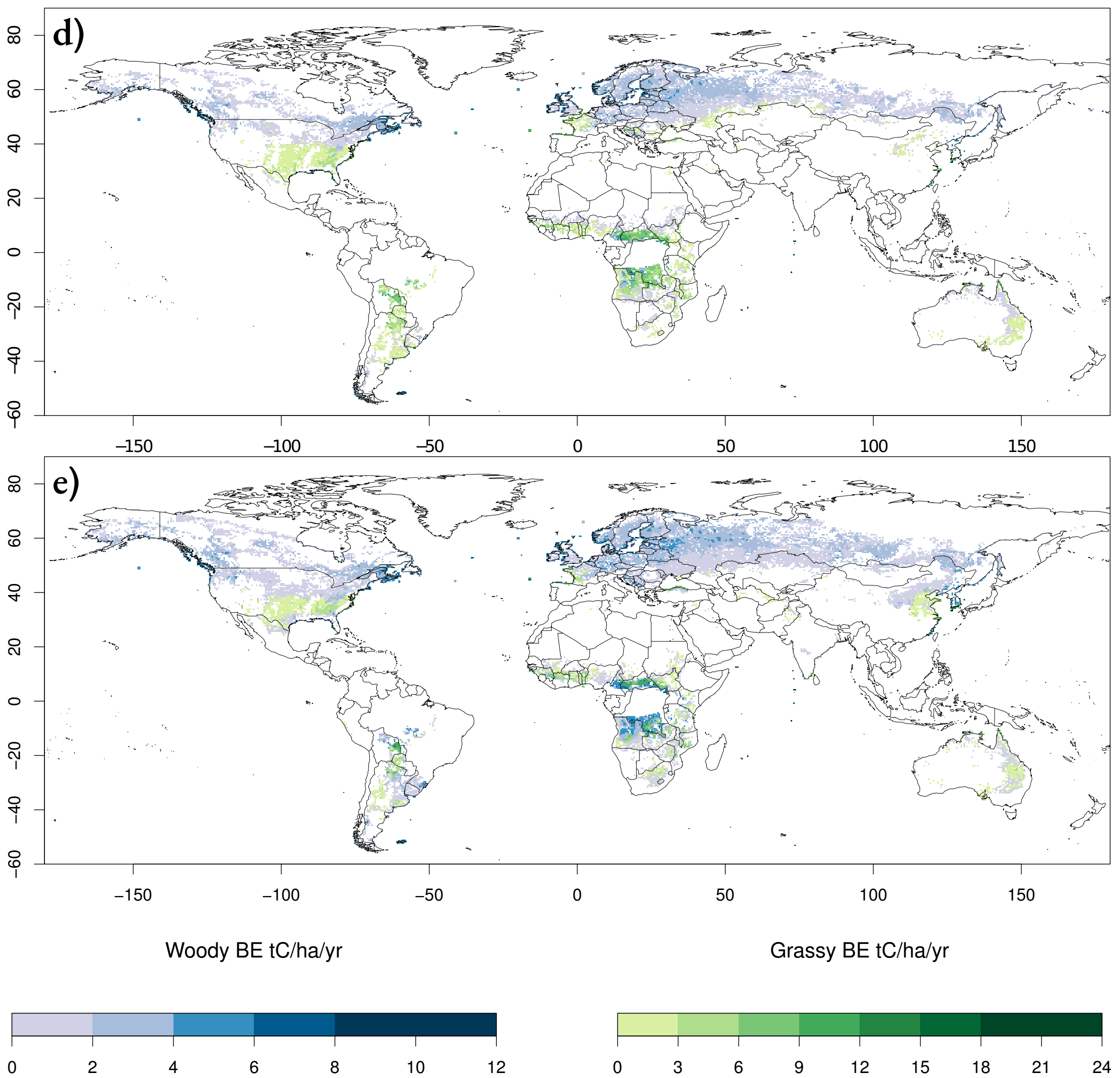


Figure B2.2: Simulated productivity and spatial distribution of woody and herbaceous BP types in the period 2090–2099, for **a)** TechUp RF, **b)** TechUp IRR, **c)** TechUp EFR, **d)** TechUp WM, **e)** IrrExp IRR.

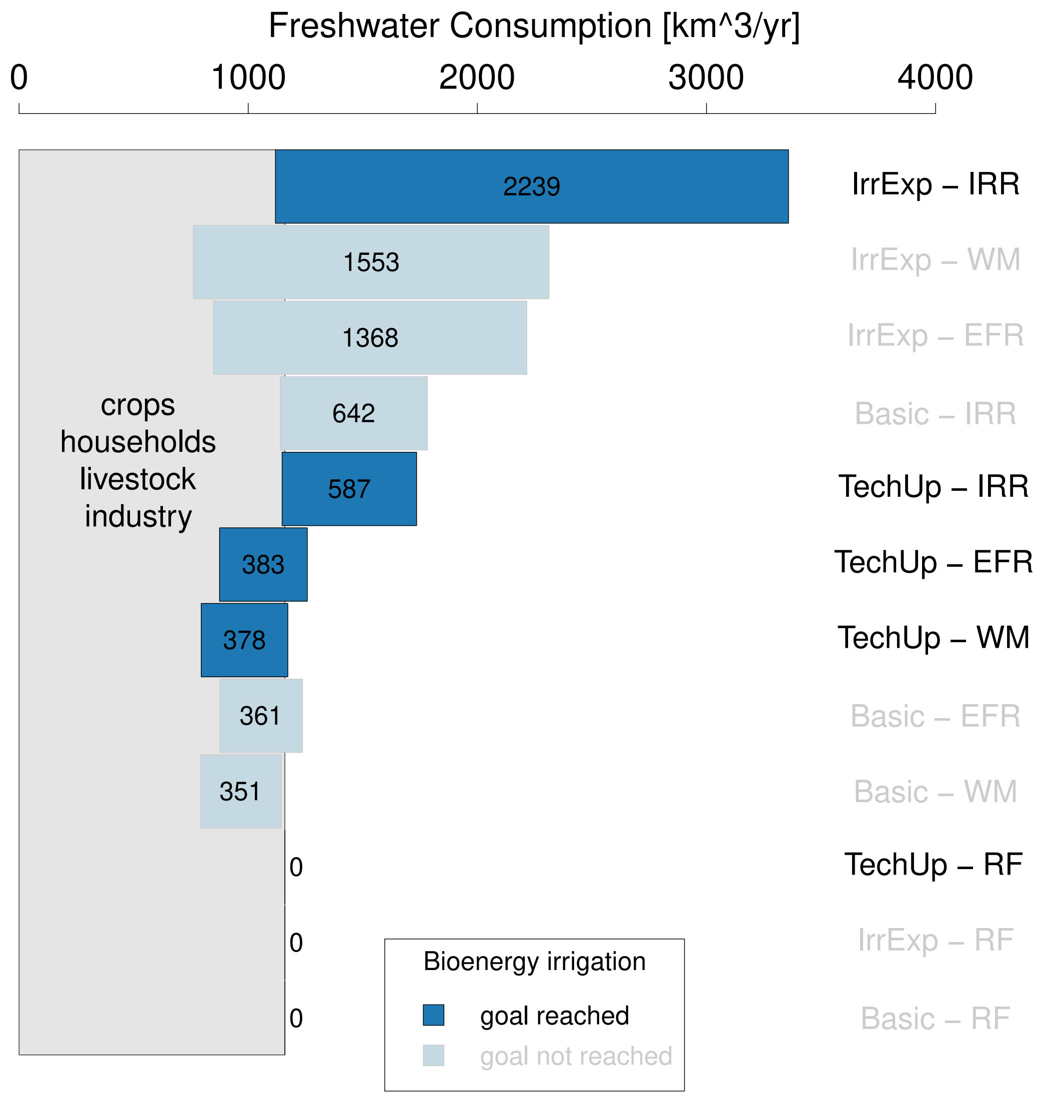


Figure B2.3: Yearly (mean 2090–2099) freshwater consumption of bioenergy plantations, agriculture, households, industry and livestock for scenarios targeting a carbon sequestration of 255 GtC.

C
Supplementary Information to P3

This supplement contains additional information, which could not be included in the main manuscript. It also includes versions of Figures from the main manuscript for all GCMs. Additionally, this supplement contains Figures based on *max. yearly stress*, defined as the WSI of the mostly stressed month in a grid cell.

Supplementary Table C3.1 displays detailed globally aggregated data for all scenarios considered as the mean of all 4 GCMs.
Supplementary Table C3.2 shows GCMs specific data for the main scenarios (Today, CC, Baseline, BECCS, and BECCS+SWM).
Supplementary Figure C3.1 shows the GCM-specific maps for Figure 5.3a.
Supplementary Figure C3.2 shows the GCM-specific maps for Figure 5.3b.
Supplementary Figure C3.3 displays the grid-cell specific max. month WSI for HadGEM2-ES.
Supplementary Figure C3.4 displays the grid-cell specific mean WSI for GFDL-ESM2M.
Supplementary Figure C3.5 displays the grid-cell specific max. month WSI for GFDL-ESM2M.
Supplementary Figure C3.6 displays the grid-cell specific mean WSI for IPSL-CM5A-LR.
Supplementary Figure C3.7 displays the grid-cell specific max. month WSI for IPSL-CM5A-LR.
Supplementary Figure C3.8 displays the grid-cell specific mean WSI for MIROC5.
Supplementary Figure C3.9 displays the grid-cell specific max. month WSI for MIROC5.
Supplementary Figure C3.10 shows the differences in water stress in future scenario CC compared to today.
Supplementary Figure C3.11 shows the differences in water stress in future scenario BECCS com-

pared to today.
Supplementary Figure C3.12 displays the precipitation differences between RCP2.6 and RCP6.0.
Supplementary Figure C3.13 shows the relative difference in area equipped for irrigation.
Supplementary Figure C3.14 displays the global crop harvest (excluding grassland, pastures, and bioenergy crops) per year for the 4 scenarios (CC, Baseline, BECCS, and BECCS+SWM) for each GCM.
Supplementary Figure C3.15 displays that adding irrigation in the BECCS scenario has little effect on harvests compared to the Baseline (the curves are virtually identical). Limiting the irrigation water withdrawals in the BECCS+SWM scenario is approximately balanced by the increased on-field water use efficiency (total crop harvests are between 3% and 5% lower), which is much smaller than the variability induced by the different climate inputs (up to 18%).
Supplementary Figure C3.16 shows the comparison of water stress drivers between scenarios BECCS+SWM and CC.
Supplementary Figure C3.17 displays the gridcell specific area shares of food crops and pastures (green) overlain with those of bioenergy (red) for IPSL-CM5A-LR.
Supplementary Figure C3.18 displays the gridcell specific area shares of food crops and pastures (green) overlain with those of bioenergy (red) for GFDL-ESM2M.
Supplementary Figure C3.19 displays the gridcell specific area shares of food crops and pastures (green) overlain with those of bioenergy (red) for MIROC5.
Supplementary Figure C3.20 is a version of Figure 5.1 including the global values for max. yearly WSI.
Supplementary Figure C3.21 shows the month with the highest WSI for scenario BECCS.
Supplementary Figure C3.22 shows stress difference for max. yearly stress similar to Figure 5.3.
Supplementary Figure C3.23 shows main driver for max. yearly stress similar to Figure 5.4.

Table C3.1: Globally aggregated biomass harvest, water withdrawals, and water stress indicators for all scenarios considered. Shown are total biomass harvest (GtC), total yearly freshwater withdrawals (domestic, industrial, irrigation of agricultural crops and bioenergy plantations; km^3/yr), as well as global area and population exposed to (very) high water stress, presented as inter-model mean derived under forcing from 4 GCMs. Water stress is analyzed for the month with maximum stress and the annual mean, respectively, for today (2006-2015), the RCP6.0 scenario representing climate change, and RCP2.6 scenarios assuming different irrigation and water management levels (2090-2099 average).

	Cumulative bioenergy harvest [GtC]	Total freshwater withdrawals [km^3/yr]	Area under WSI>40% in at least one month [Mha]	Population under WSI>40% in at least one month [Mio]	Area under WSI>40% in the yearly mean [Mha]	Population under WSI>40% in the yearly mean [Mio]
Today	0	3456	2250	3786	1023	2284
RCP6.0 0%	15	4707	2975	5978	1487	3997
RCP6.0 30% (*CC*)	15	4861	3096	6163	1580	4146
RCP2.6 0% (*Baseline*)	296	4571	2946	6043	1508	4109
RCP2.6 15%	309	4706	3488	6391	1784	4412
RCP2.6 30% (*BECCS*)	344	5231	3738	6486	1928	4583
RCP2.6 45%	374	5676	3890	6539	2018	4660
RCP2.6 60%	402	6063	4010	6571	2094	4702
RCP2.6 30% EFR	318	3705	2704	5811	1192	3655
RCP2.6 45% EFR	336	3935	2792	5904	1225	3708
RCP2.6 60% EFR	353	4134	2866	5952	1253	3753
RCP2.6 90% EFR	379	4459	2946	5998	1288	3788
RCP2.6 30% EFR WM	327	3675	2754	5872	1186	3605
RCP2.6 45% EFR WM (*BECCS+SWM*)	346	3913	2855	5949	1224	3661
RCP2.6 60% EFR WM	363	4120	2926	6006	1252	3703
RCP2.6 90% EFR WM	391	4457	3014	6060	1291	3759

Table C3.2: GCM-specific results for the main scenarios from Table C3.1.

	Cumulative bioenergy harvest [GtC]	Total freshwater withdrawals [km^3/yr]	Area under WSI>40% in at least one month [Mha]	Population under WSI>40% in at least one month [Mio]	Area under WSI>40% in the yearly mean [Mha]	Population under WSI>40% in the yearly mean [Mio]
Today HadGEM2-ES	0	3491	2172	3751	982	2229
Today MIROC5	0	3519	2318	3857	1065	2322
Today GFDL-ESM2M	0	3417	2273	3748	1026	2273
Today IPSL-CM5A-LR	0	3396	2237	3786	1020	2312
CC HadGEM2-ES	14	5047	3151	6276	1579	4242
CC MIROC5	18	4845	3024	6047	1520	4025
CC GFDL-ESM2M	13	4819	3158	6258	1607	4161
CC IPSL-CM5A-LR	14	4733	3051	6072	1613	4156
Baseline HadGEM2-ES	310	4618	2985	6072	1537	4203
Baseline MIROC5	313	4637	2955	5953	1523	4126
Baseline GFDL-ESM2M	273	4476	2909	6084	1481	4048
Baseline IPSL-CM5A-LR	290	4554	2936	6064	1490	4061
BECCS HadGEM2-ES	355	5238	3750	6493	1938	4647
BECCS MIROC5	359	5318	3803	6470	1970	4705
BECCS GFDL-ESM2M	318	5105	3653	6512	1901	4520
BECCS IPSL-CM5A-LR	342	5265	3747	6470	1903	4460
BECCS+SWM HadGEM2-ES	358	3984	2884	5987	1224	3787
BECCS+SWM MIROC5	364	4146	3010	6096	1327	3851
BECCS+SWM GFDL-ESM2M	318	3695	2734	5849	1167	3472
BECCS+SWM IPSL-CM5A-LR	343	3827	2792	5867	1178	3534

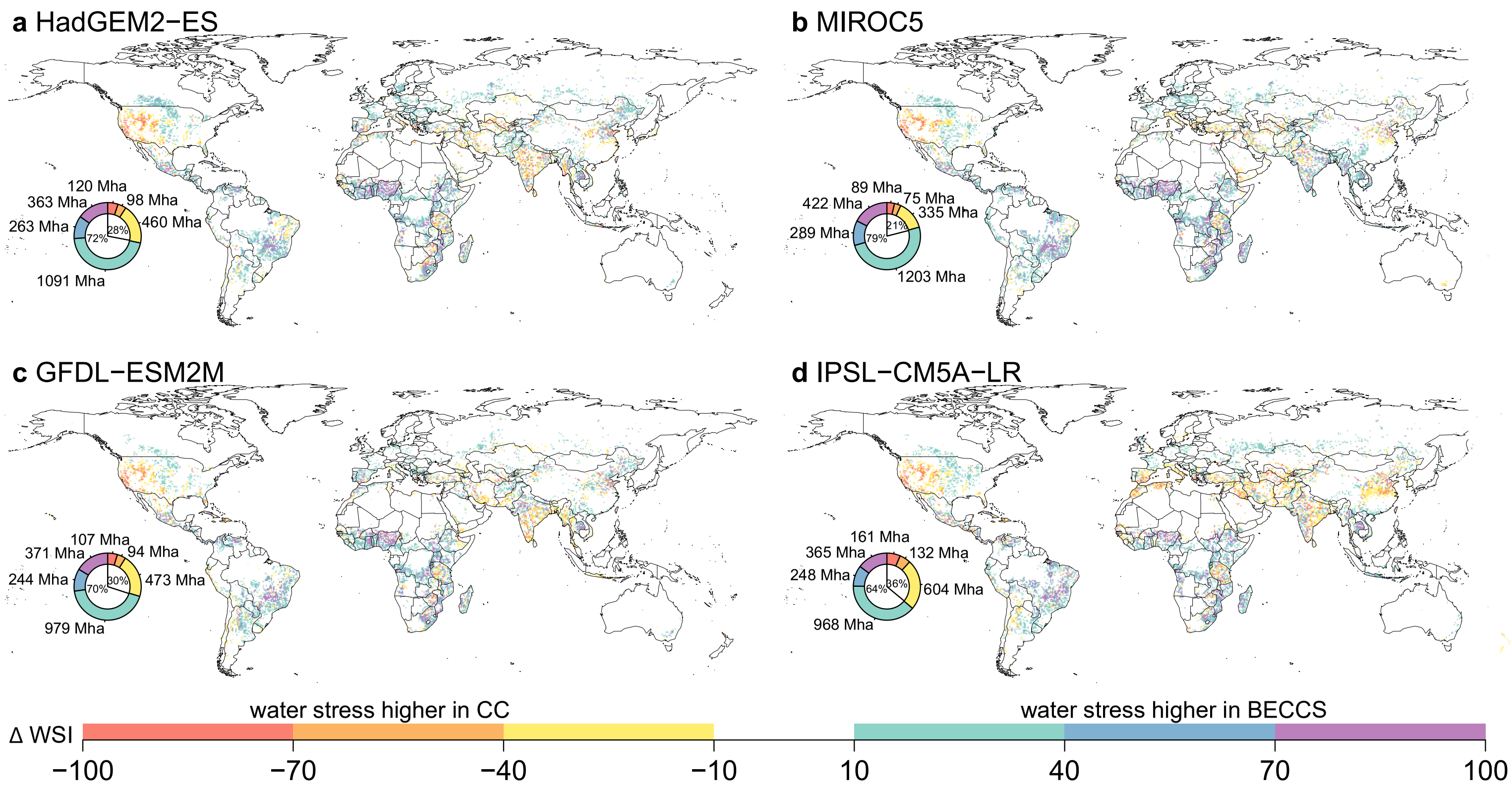


Figure C3.1: As Figure 5.3a, but for all four GCMs.

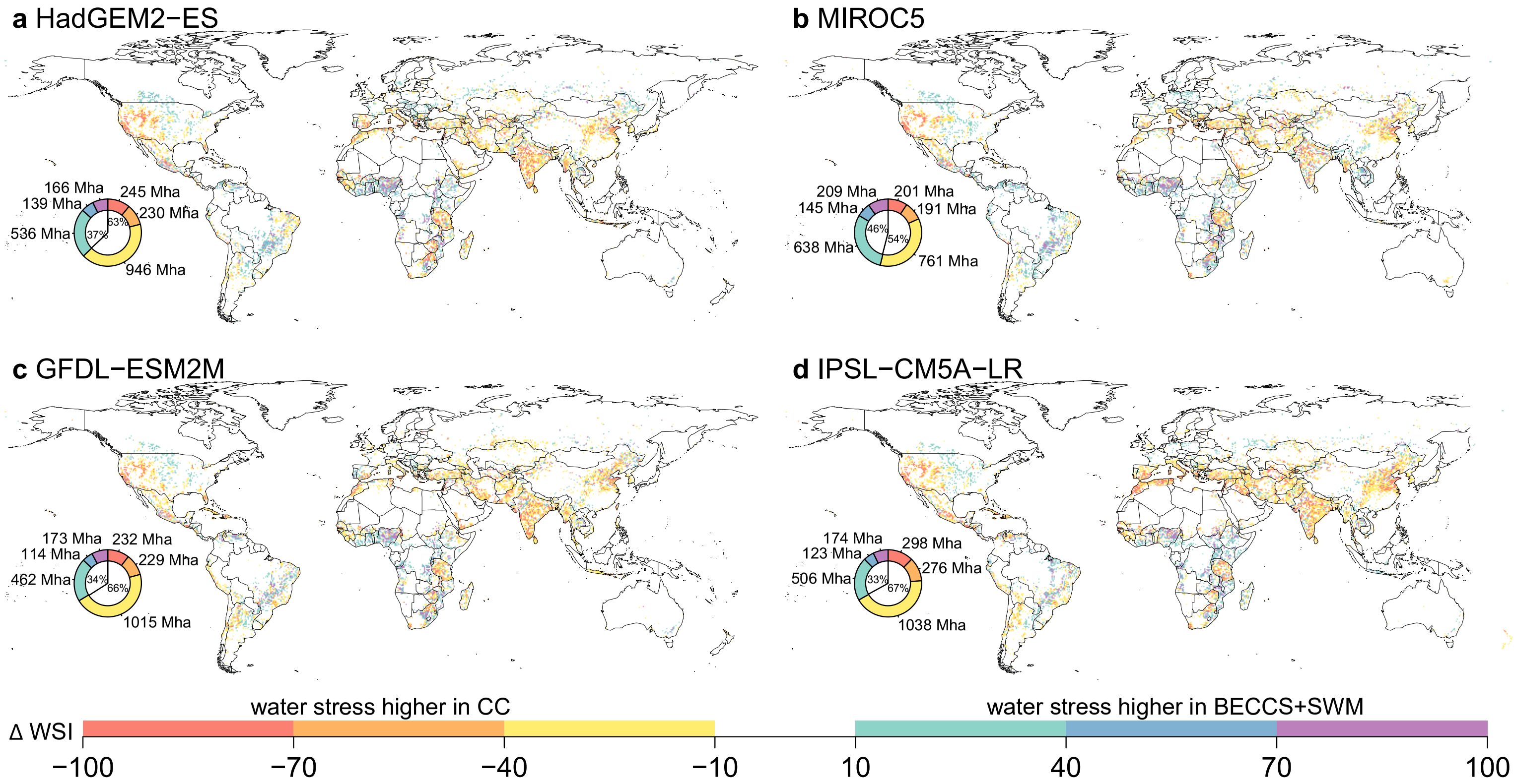


Figure C3.2: As Figure 5.3b, but for all four GCMs.

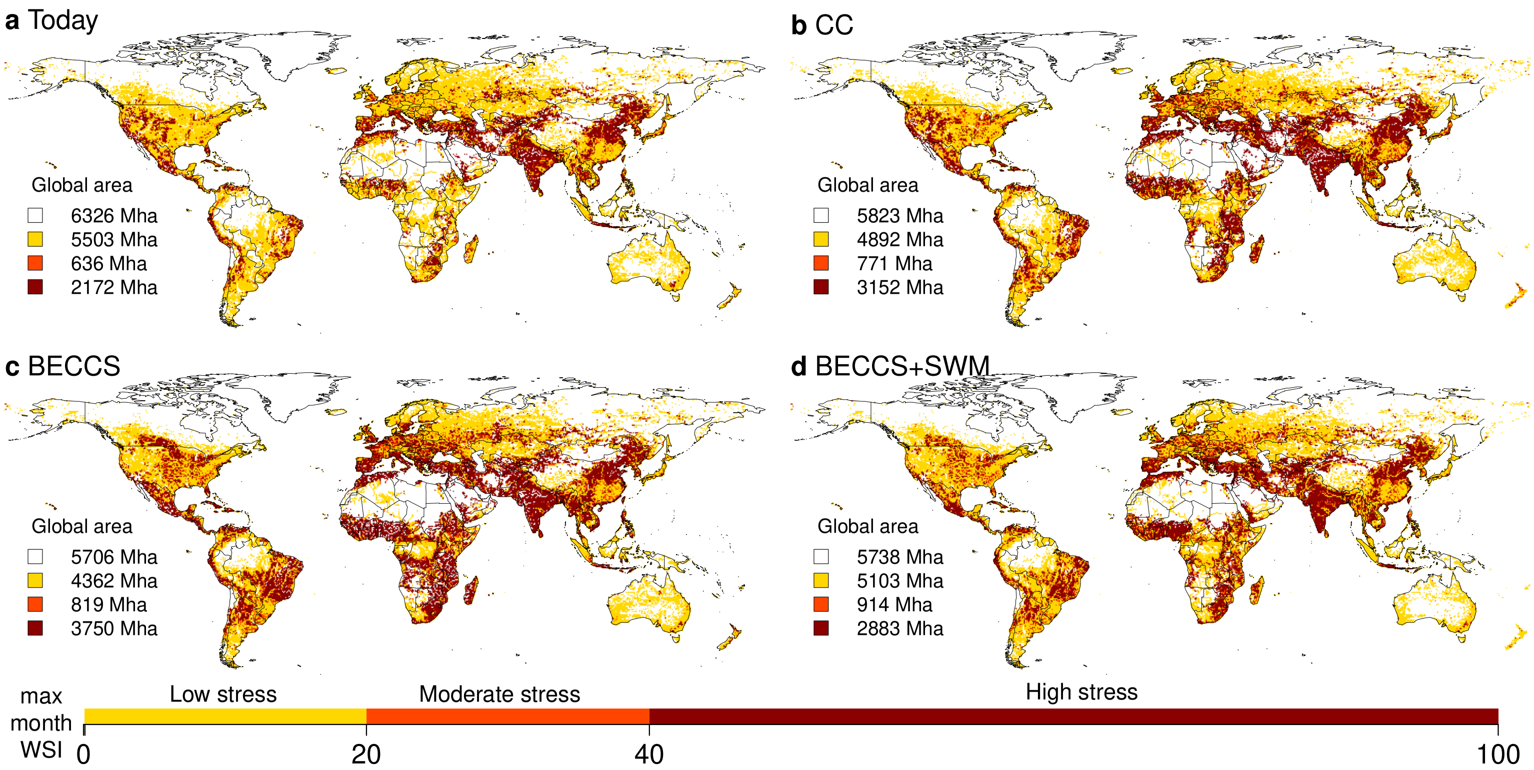


Figure C3.3: As Figure 5.2, but for the water stress in the maximum month (HadGEM2-ES).

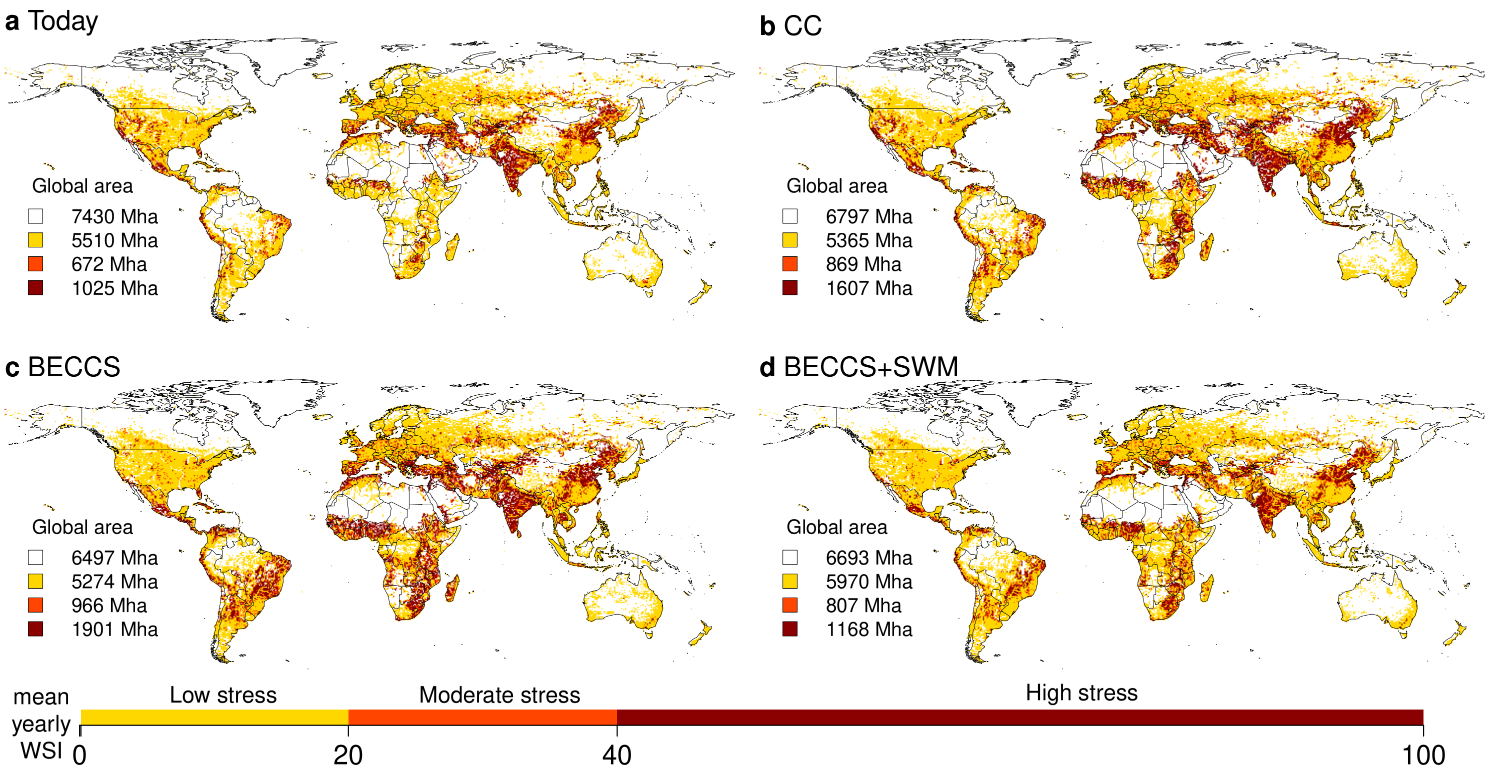


Figure C3.4: As Figure 5.2 and Figure C3.3, but for GFDL-ESM2M.

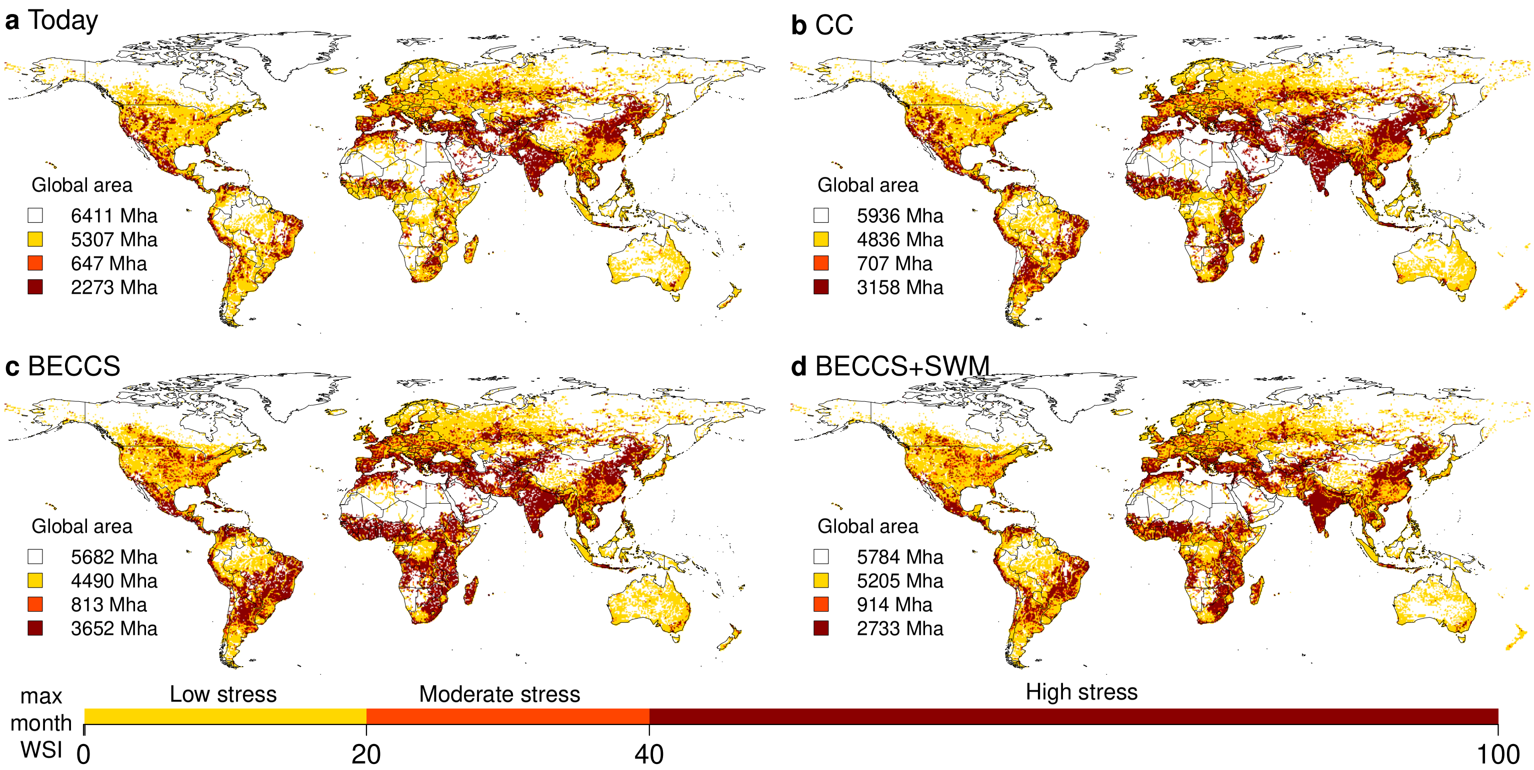


Figure C3.5: As Figure 5.2 and Figure C3.3, but for maximum month water stress in GFDL-ESM2M.

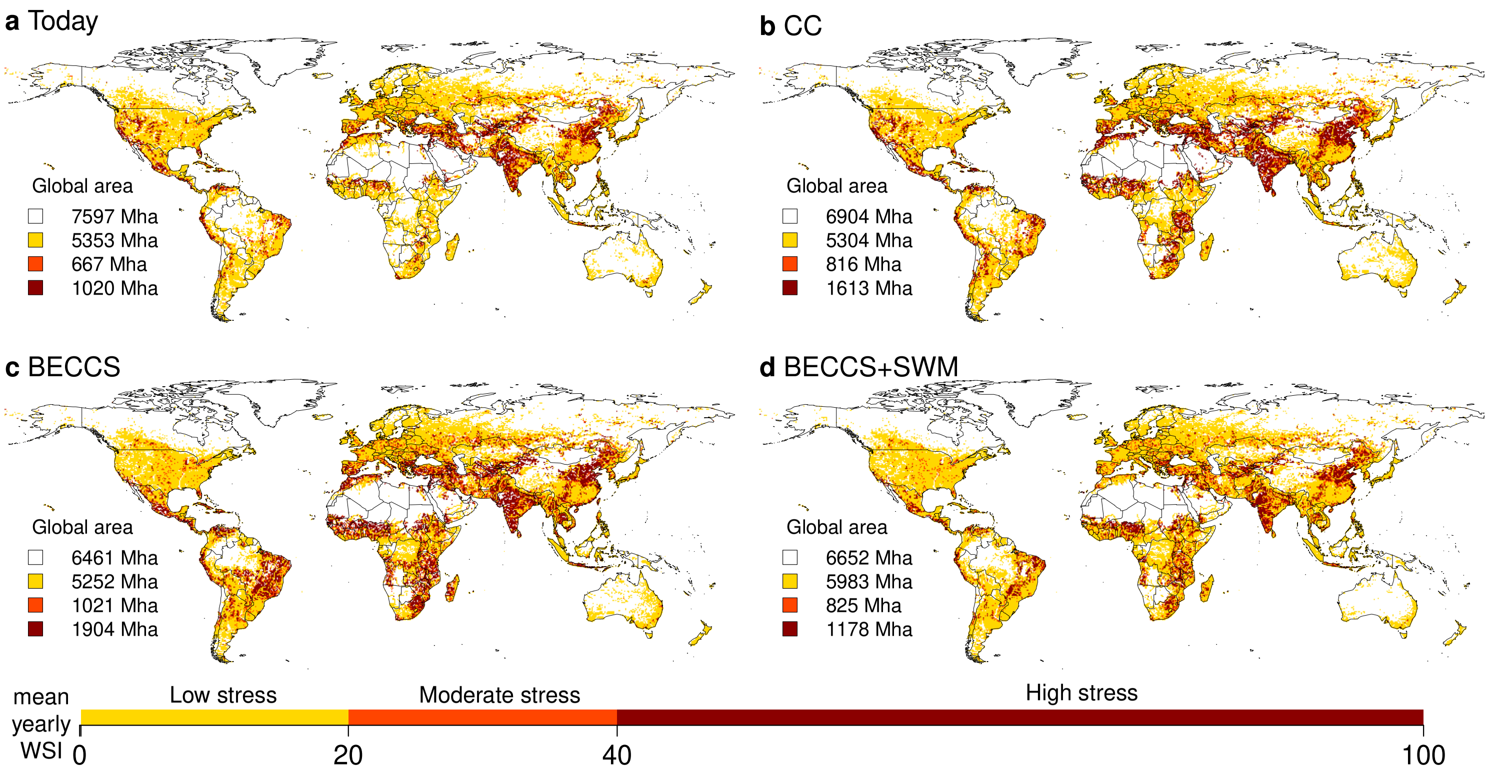


Figure C3.6: As Figure 5.2 and Figure C3.3, but for IPSL-CM5A-LR.

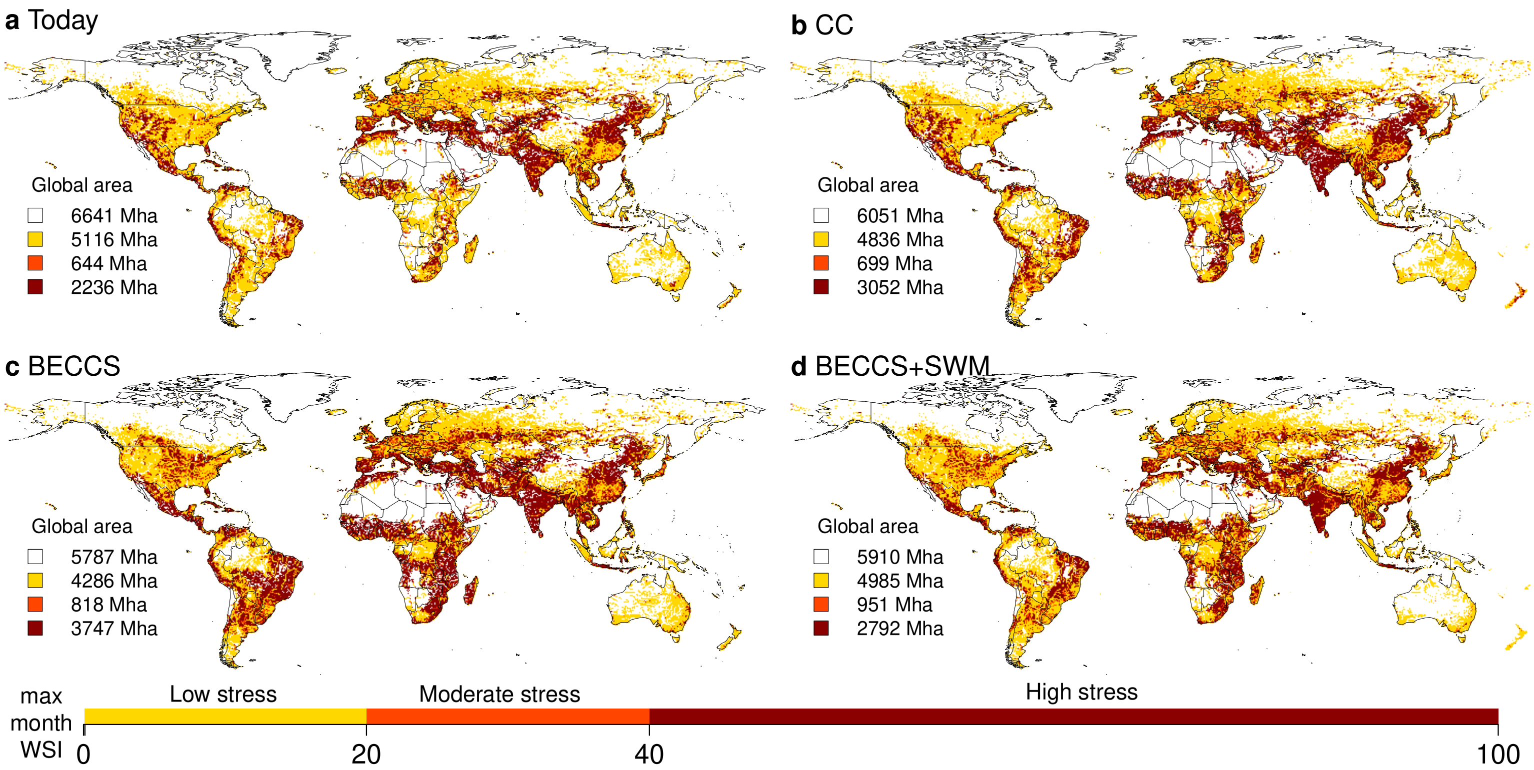


Figure C3.7: As Figure 5.2 and Figure C3.3, but for maximum month water stress in IPSL-CM5A-LR.

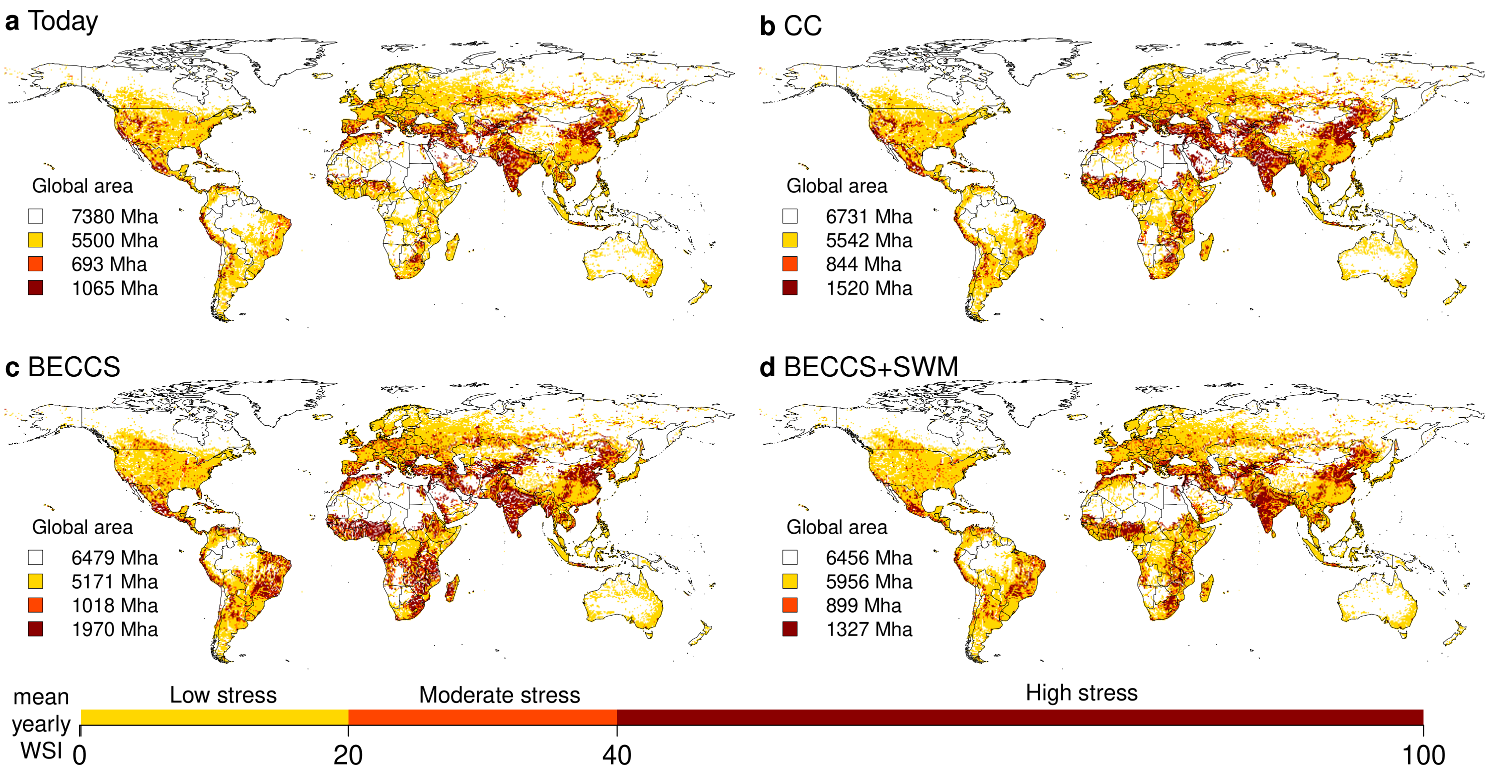


Figure C3.8: As Figure 5.2 and Figure C3.3, but for MIROC5.

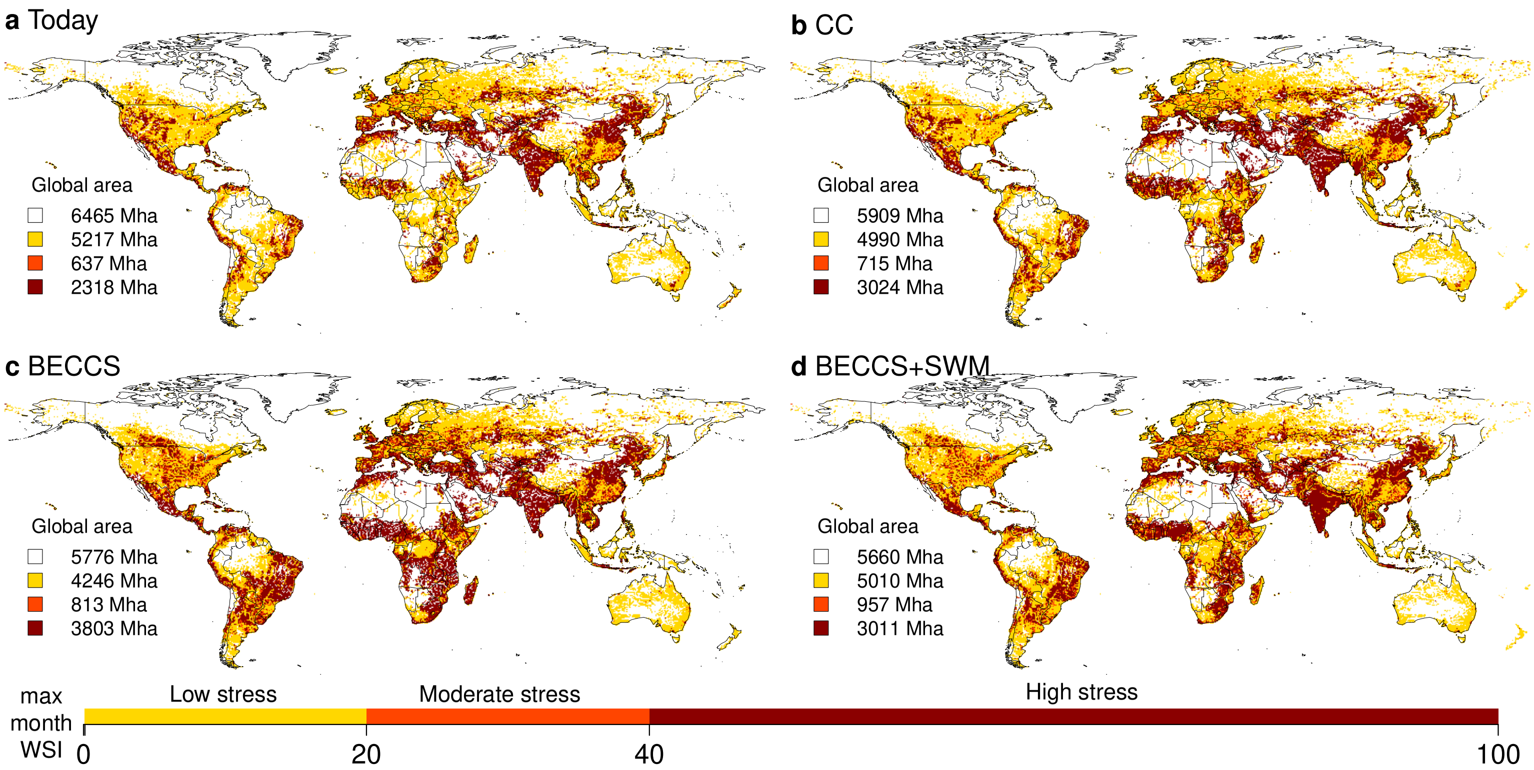


Figure C3.9: As Figure 5.2 and Figure C3.3, but for maximum month water stress in MIROC5.

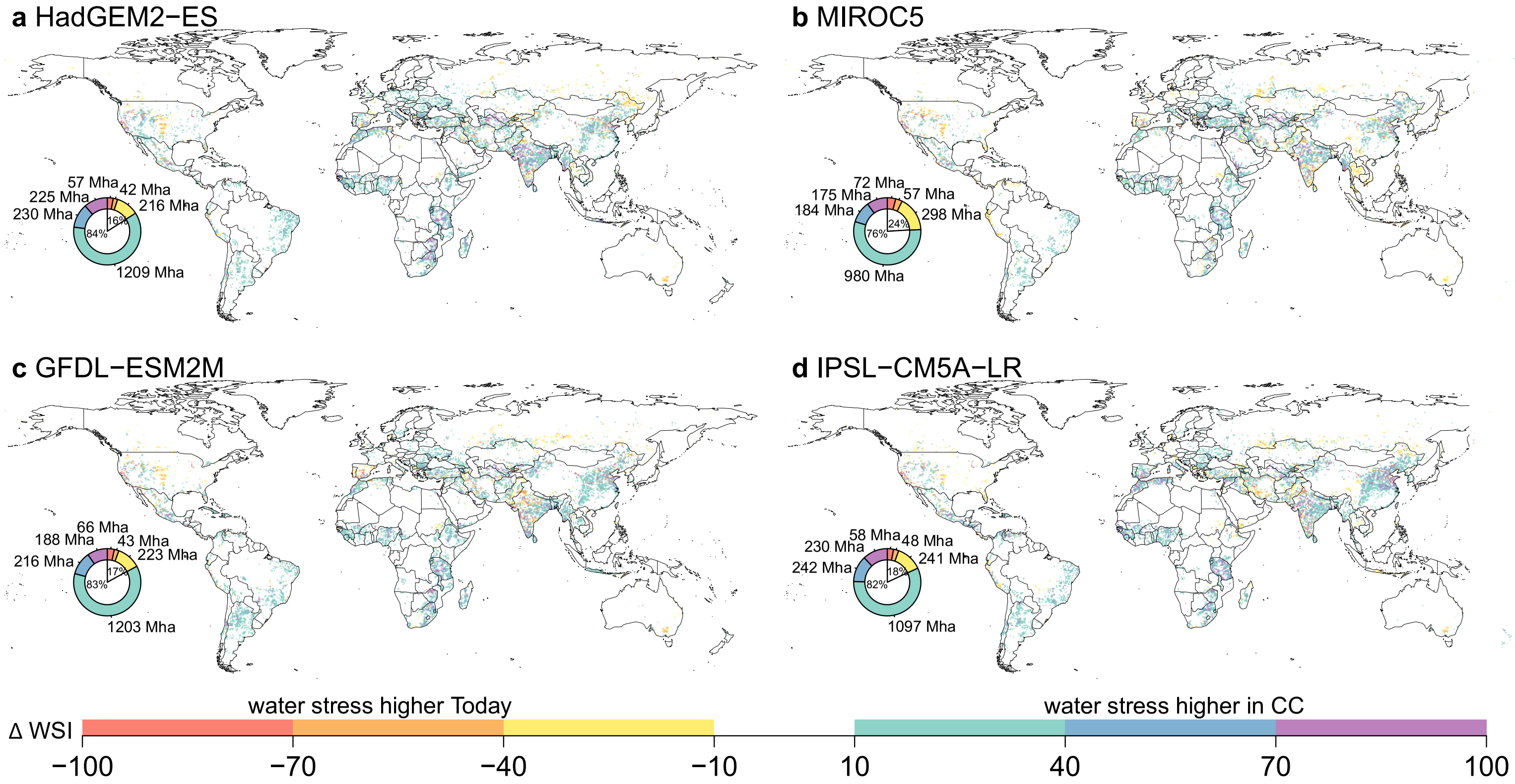


Figure C3.10: Differences in water stress in future scenario CC compared to today. Shown are differences in WSI values for all four GCMs (2090-2099 average) in comparison to present conditions (2006-2015 average). Pie diagrams show the total area of each color-class.

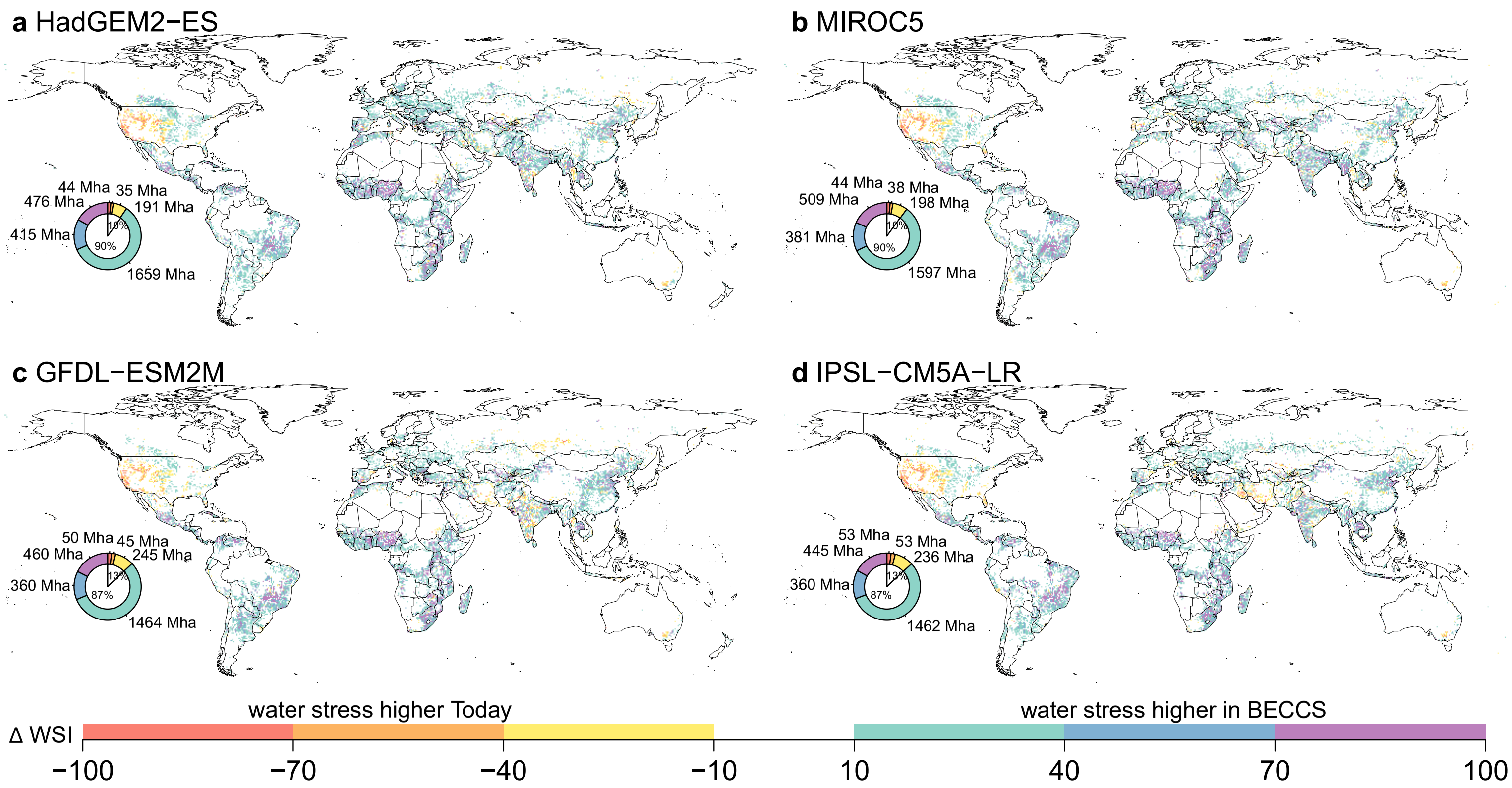


Figure C3.11: Differences in water stress in future scenario BECCS compared to today. As Figure C3.10, but comparing WSI in scenario BECCS with today.

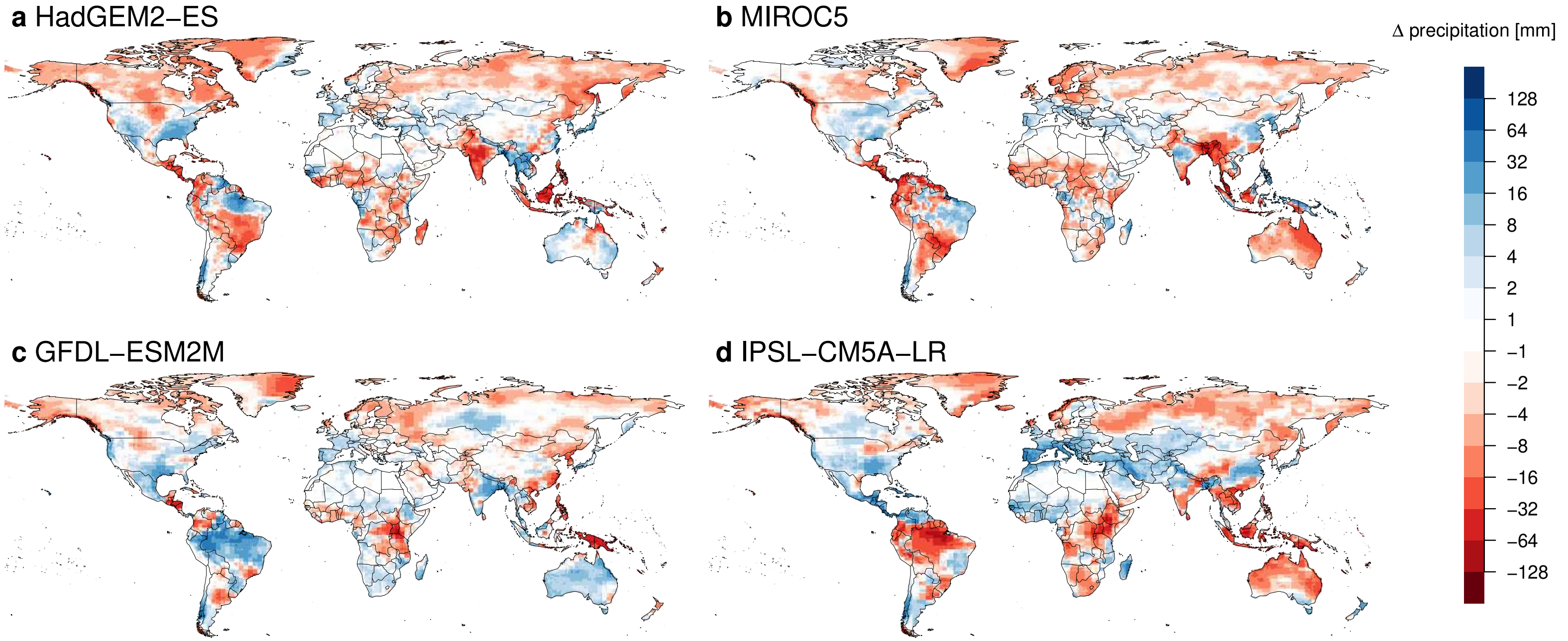


Figure C3.12: Precipitation differences between RCP2.6 and RCP6.0 for the 4 GCMs considered. Shown are the absolute differences of the mean yearly precipitation from 2090–2099 provided by the ISMIP2b project. Blue locations show higher precipitation in RCP2.6 and red locations in RCP6.0.

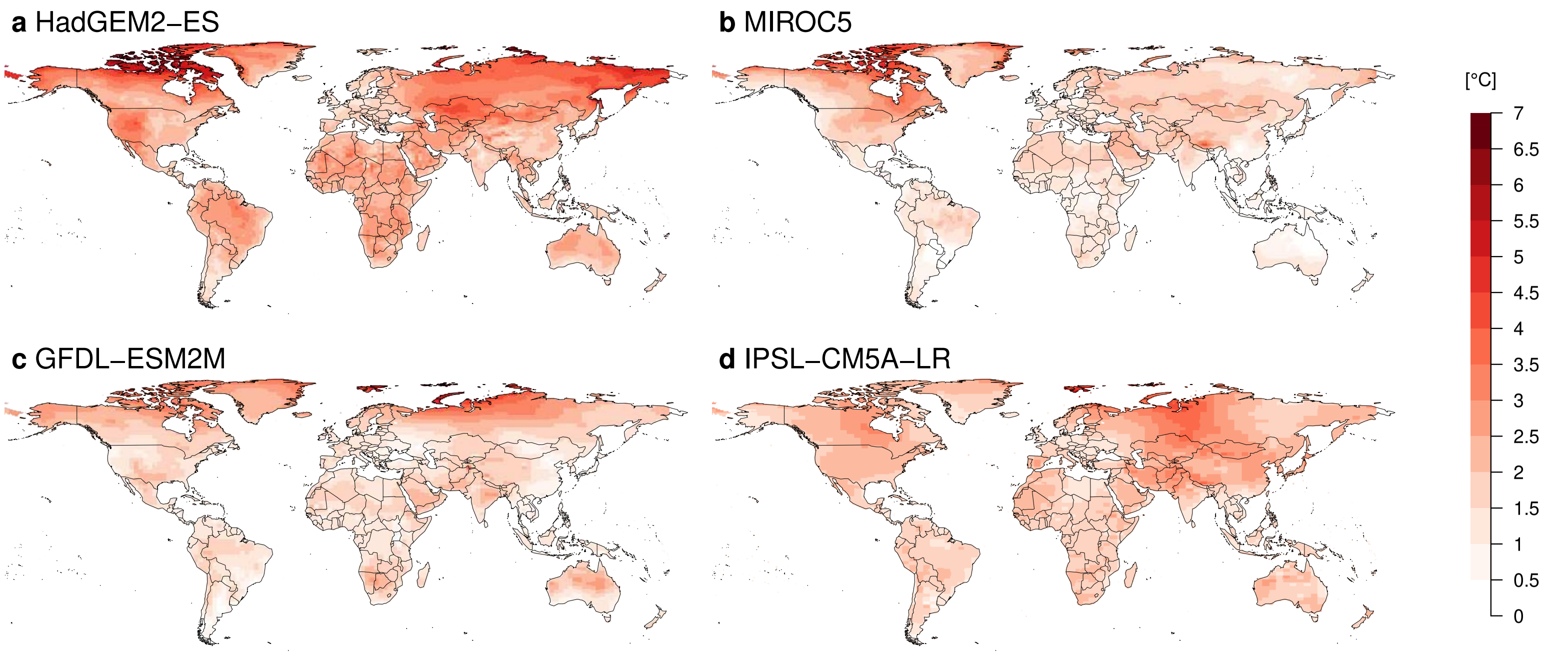


Figure C3.13: Mean yearly Temperature difference (2090-2099) between RCP6.0–RCP2.6 for all four GCMs. Data from ISIMIP2b project.

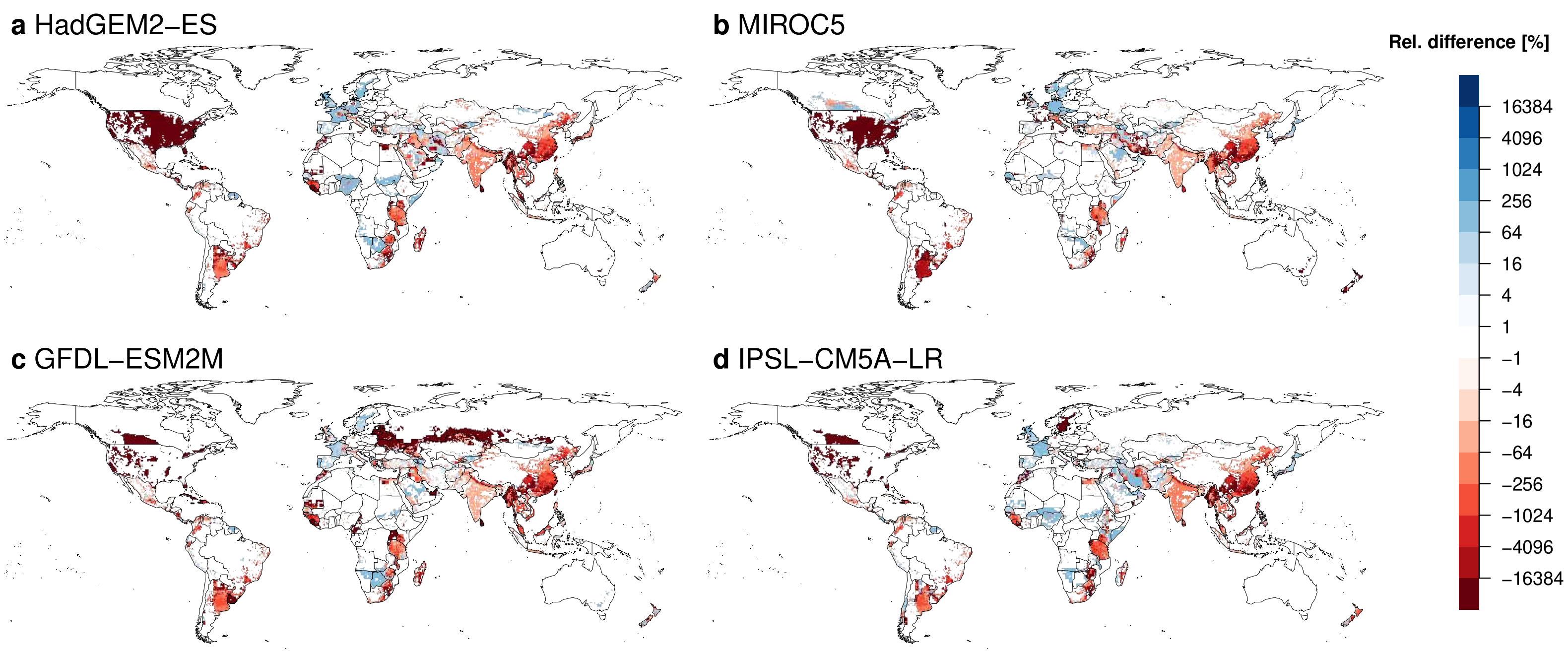


Figure C3.14: Relative difference in area equipped for irrigation: (RCP2.6–RCP6.0)/RCP2.6x100. Difference of grid-cell specific sum of area equipped for irrigation (crops and pastures, excluding bioenergy crops) in 2095 (ISMIP2b) between RCP2.6 and RCP6.0 for all GCMs. Blue represents locations with larger irrigated areas in RCP2.6, while red locations show larger irrigated areas in RCP6.0.

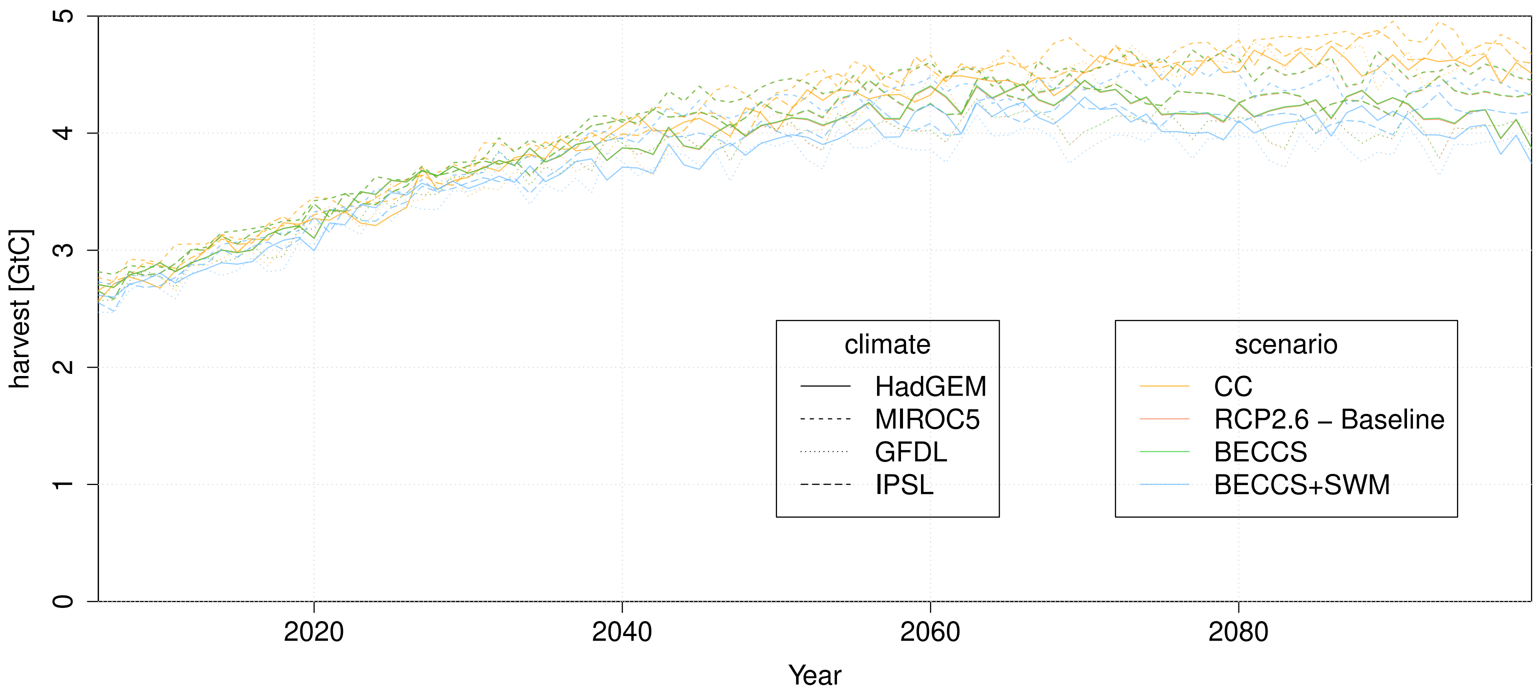


Figure C3.15: Global crop harvest (excluding grassland, pastures, and bioenergy crops) per year for scenarios *CC*, *RCP2.6 - Baseline*, *BECCS*, and *BECCS+SWM* for the GCMs HadGEM2-ES, MIROC5, GFDL-ESM2M and IPSL-CM5A-LR. The harvest is calculated as the cft-specific LPJmL yield multiplied with the assumed productivity increases from MAgPIE. Values for *RCP2.6 - Baseline* and *BECCS* are virtually identical.

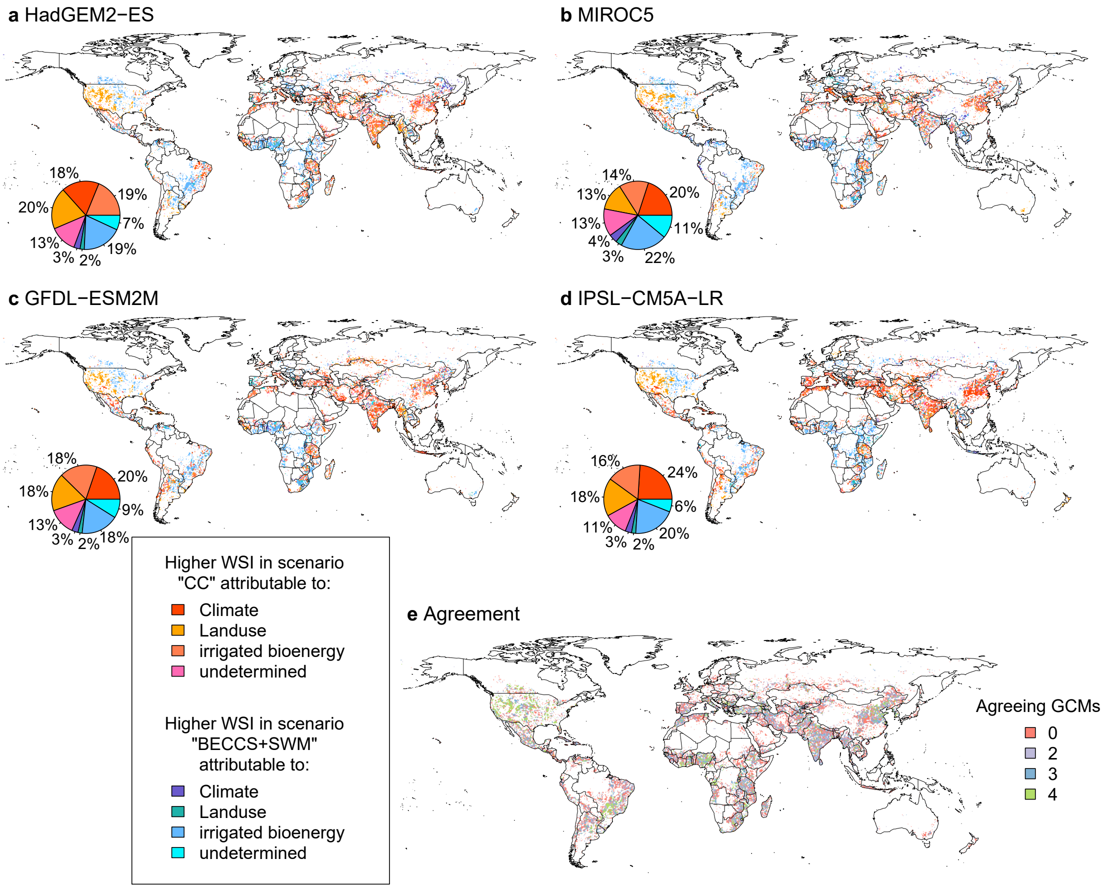


Figure C3.16: As Figure 5.4, but showing the comparison of water stress between scenarios *BECCS+SWM* and *CC*.

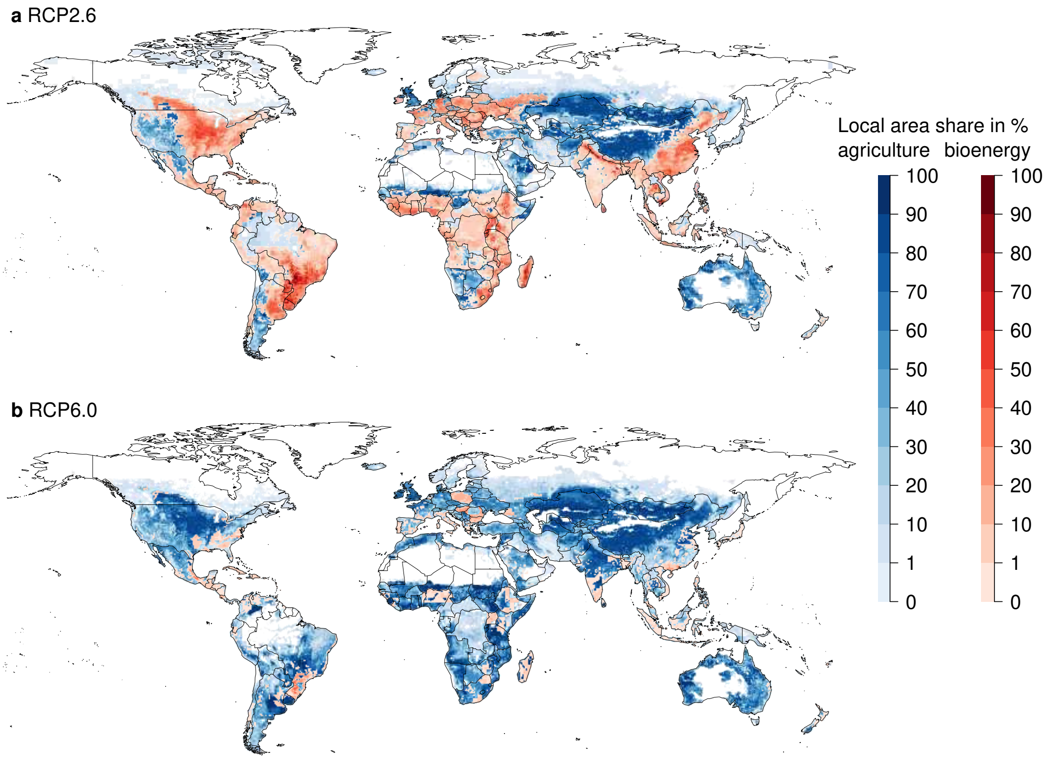


Figure C3.17: Grid cell area shares of food crops and pastures (green) overlain with those of bioenergy (red) for 2090-2099 in the associated land use scenarios for RCP2.6 and RCP6.0 (623/32 Mha) in ISIMIP2b for the GCM IPSL-CM5A-LR.

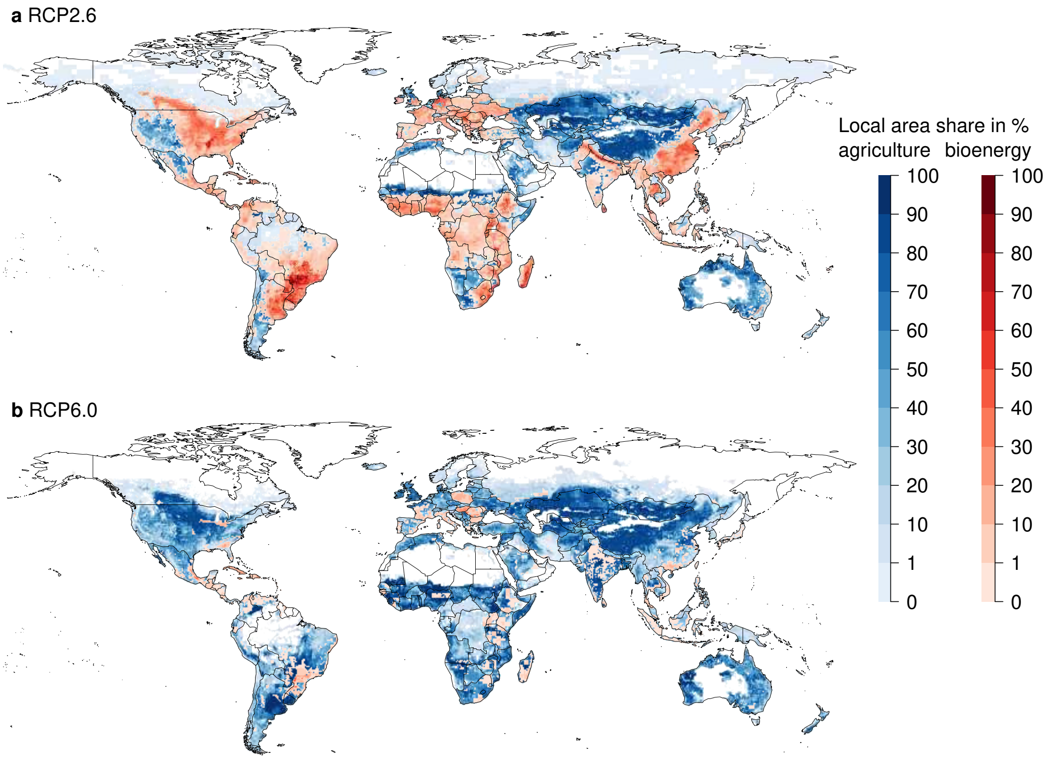


Figure C3.18: Grid cell area shares of food crops and pastures (green) overlain with those of bioenergy (red) for 2090-2099 in the associated land use scenarios for RCP2.6 and RCP6.0 ($596/28\,\mathrm{Mha}$) in ISIMIP2b for the GCM GFDL-ESM2M.

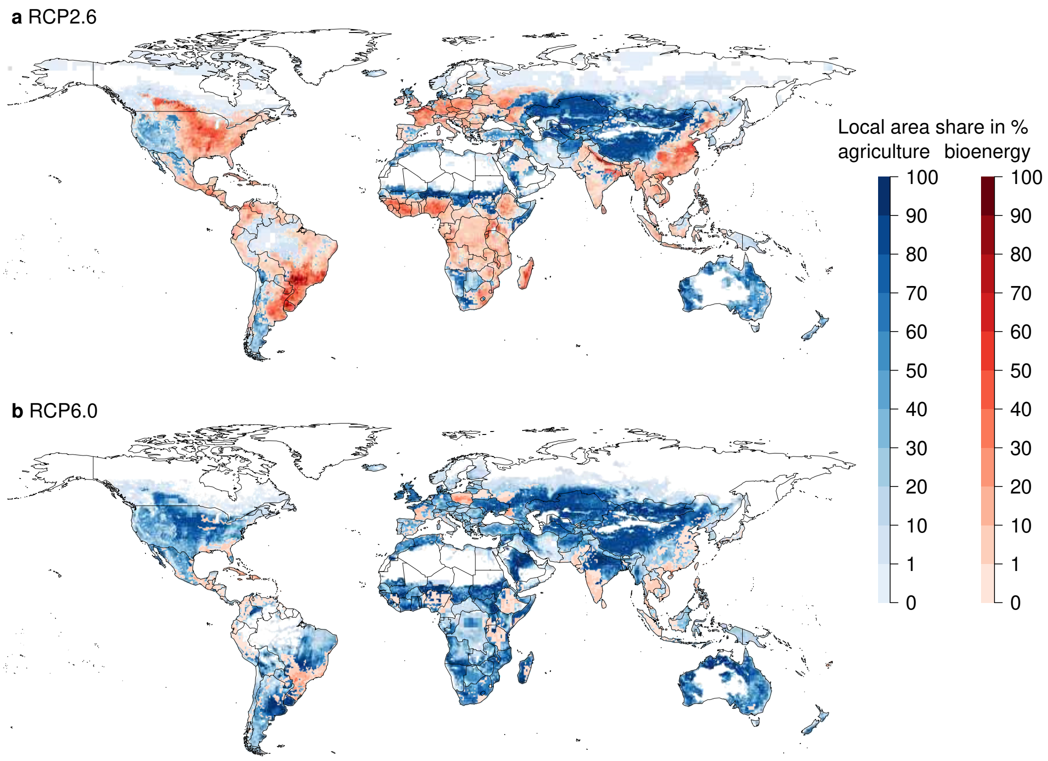


Figure C3.19: Grid cell area shares of food crops and pastures (green) overlain with those of bioenergy (red) for 2090-2099 in the associated land use scenarios for RCP2.6 and RCP6.0 (592/32 Mha) in ISIMIP2b for the GCM MIROC5.

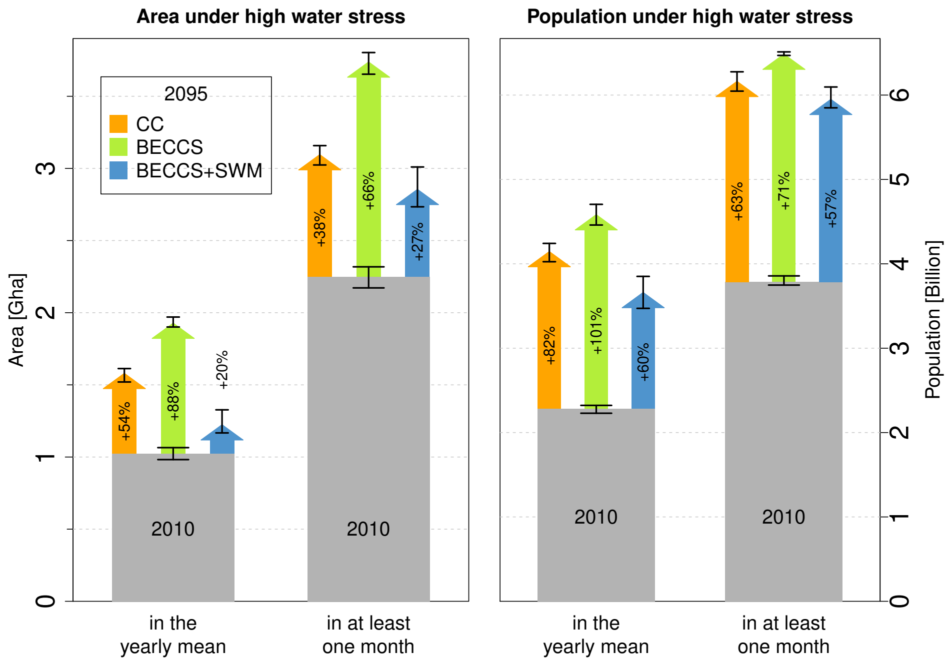


Figure C3.20: Simulated increase of area and population exposed to high water stress from 2010 (2006-2015) to 2095 (2090-2099) in the different scenarios. The numbers represent global sums of grid cell-level area and population, respectively, where annual mean WSI>40% (left bars of each panel), or where WSI>40% in at least one month per year – max. month (right bars). Shown are the mean change and the ranges resulting from the differences in climate simulations based on the four GCMs. Grey bars represent the current (2006-2015 average) levels.

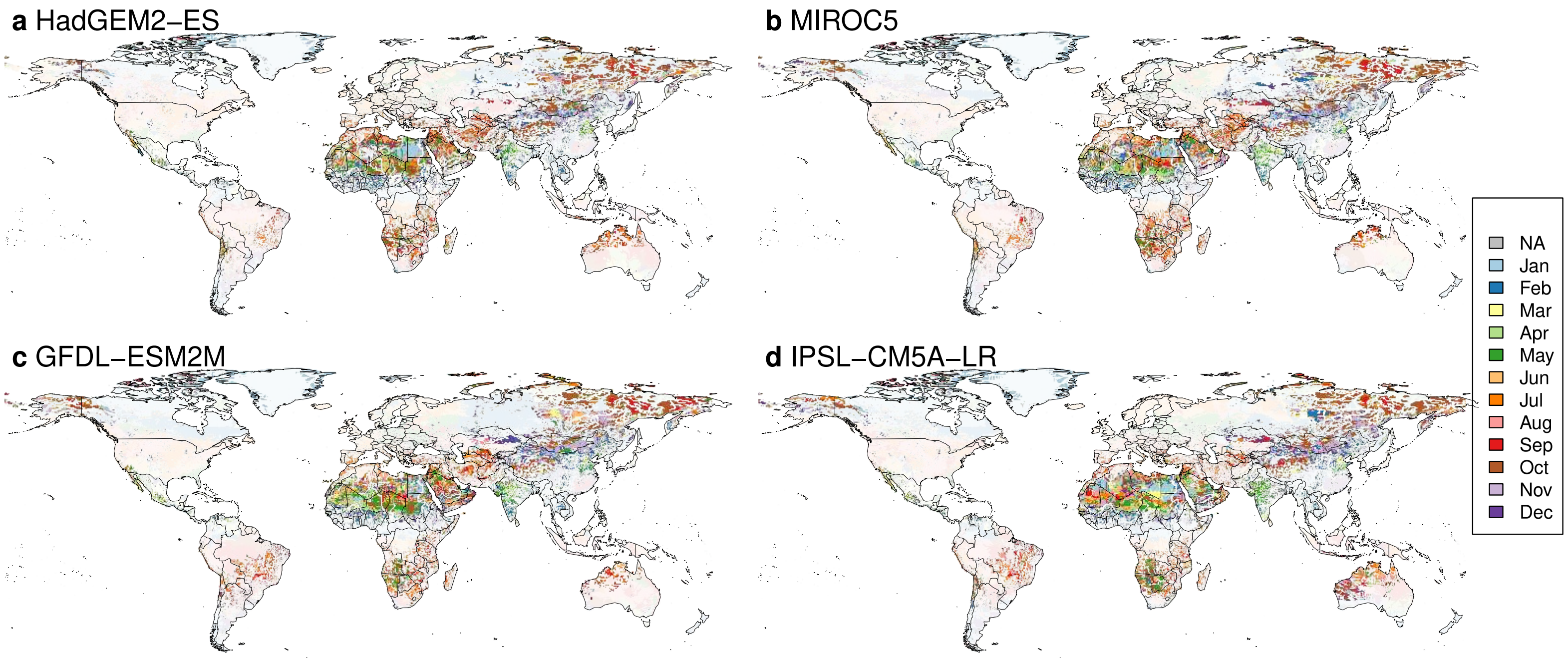


Figure C3.21: Month with max. water stress for 2090-2099 in scenario *BECCS*. Five transparency levels are based on the local grid cell WSI (0-100%), whereby colors have no transparency (0) for WSI 70-100% and high transparency (0.9) for 0-20%. Intermediate steps are WSI 20-40% (transparency 0.7) and 40-70% (transparency 0.4).

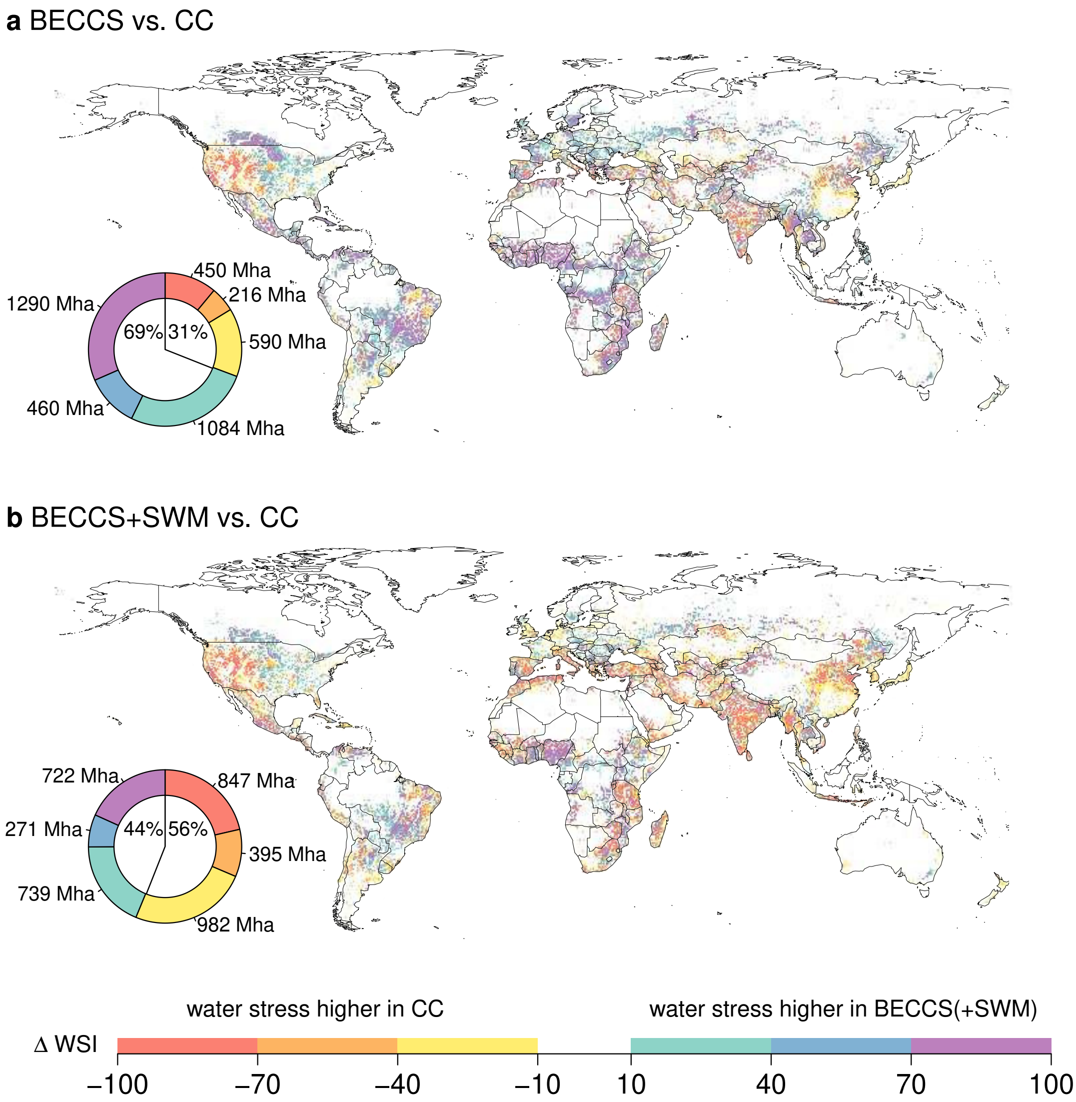


Figure C3.22: Differences in peak water stress between scenarios BECCS(+SWM) and CC. As Figure 5.3, but for max. yearly water stress. Shown are differences in mean yearly WSI values (percentage points) among the different scenarios (here, under HadGEM2 climate forcing, 2090-2099 average). Pie diagrams show the total global area showing a certain (respectively colored) difference.

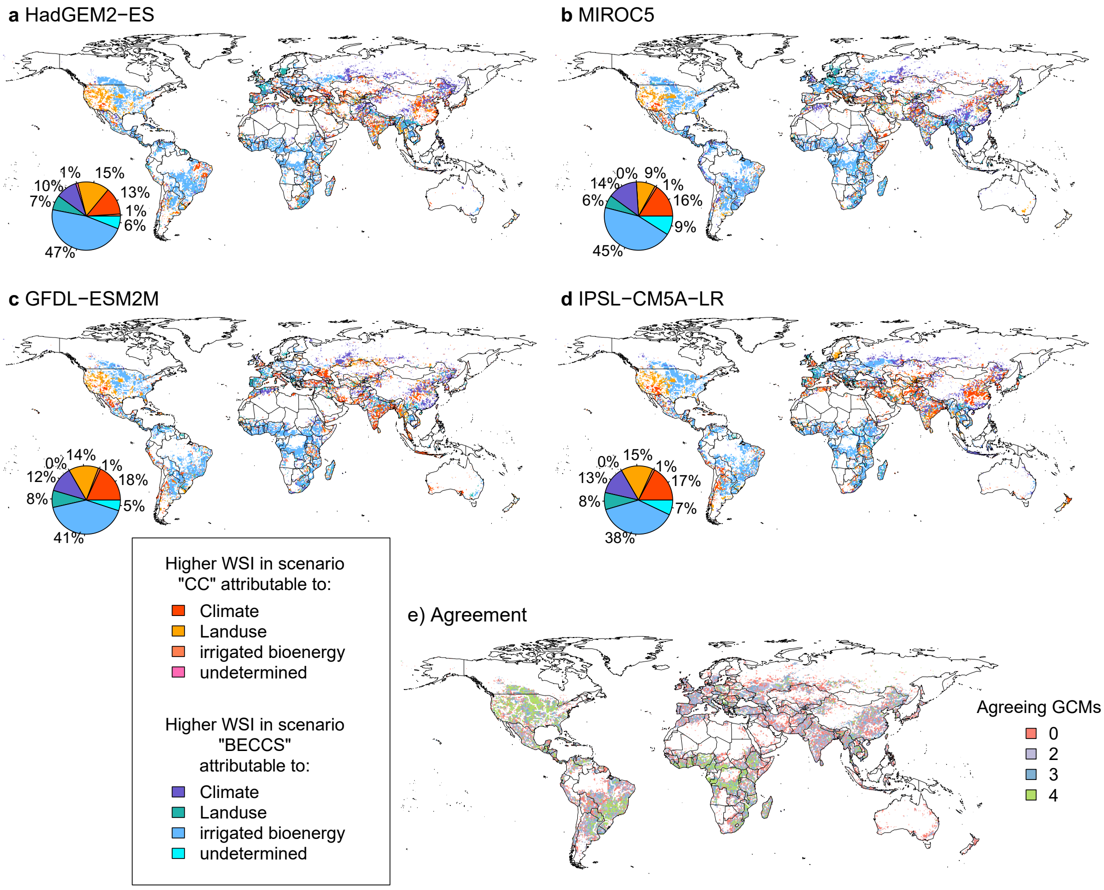


Figure C3.23: Attribution of main driver explaining differences in peak water stress between the scenarios *BECCS* and *CC*. As Figure 5.4, but for max. yearly water stress. (a-d) Higher water stress in *BECCS* is indicated by blueish colors, the opposite in reddish colors. Drivers are attributed by factorial simulation experiments keeping either land use, climate or irrigation on biomass plantations constant (see Supplementary Online Methods – Attribution of drivers for water stress differences). The global area shares of each category are displayed to the bottom-left of each map. (e) Number of GCMs that agree on the attributed driver in a grid cell.

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